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Muscle response to pneumatic hand tool torque reaction forces

ROBERT G. RADWIN

Department of Industrial Engineering,
University of Wisconsin, Madison, WI 53706, USA

ERNST VANBERGEIJK

Body & Assembly Operations,
Ford Motor Company, Dearborn, MI 48121, USA

and THOMAS J. ARMSTRONG

Center for Ergonomics,
The University of Michigan, Ann Arbor, MI 48109, USA

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Surface electromyography was used for studying the effects of torque reaction force acting against the hand, on forearm muscle activity and grip force for five subjects operating right angle, air shut-off nutrunners. Four tools having increasing spindle torque were operated using short and long torque reaction times. Nutrunner spindle torque ranged between 30 Nm and 100 Nm. Short torque reaction time was considered 0·5 s while long torque reaction time was 2 s. Peak horizontal force was the greatest component of the reaction force acting against the hand and accounted for more than 97% of the peak resultant hand force. Peak hand force increased from 89 N for the smallest tool to 202 N for the largest tool. Forearm muscle rms EMG, scaled for grip force, indicated average flexor activity during the Torque-reaction phase was more than four times greater than the Pre-start and Post Shut-off phases, and two times greater than the Run-down phase. Flexor EMG activity during the Torque-reaction phase increased for increasing tool peak spindle torque. Average flexor rms EMG activity, scaled for grip force, during the Torque-reaction phase increased from 372 N for the 30 Nm nutrunner to 449 N for the 100 Nm nutrunner. Flexor rms EMG activity averaged during the Torque-reaction phase and scaled for grip force was 390 N for long torque reaction times and increased to 440 N for short torque reaction times. Flexor rms EMG integrated over the torque reaction phase was 839 Ns for long torque reaction times and decreased to 312 Ns for short torque reaction times. The average latency between tool spindle torque onset and peak initial flexor rms EMG for long torque reaction times was 294 ms which decreased to 161 ms for short torque reaction times. The average latency between peak tool spindle torque, just prior to tool shut-off, and peak final rms EMG for long torque reaction times was 97 ms for flexors and 188 ms for extensors, which decreased for short torque reaction times to 47 ms for flexors and 116 ms for extensors. The results suggest that right angle nutrunner torque reaction forces can affect extrinsic hand muscles in the forearm, and hence grip exertions, by way of a reflex response. These effects may be controlled by designing hand tools that minimize torque reaction forces transmitted to the hand using mechanical advantages provided from increased handle lengths, torque reaction bars or torque absorbing suspension systems, or minimizing muscle responses to rapid torque build-up by reducing tool spindle rotation speed.

1. Introduction

Nutrunners are power hand tools used for rotational securing threaded fasteners such as screws and bolts. Pneumatic nutrunners are used extensively in automobile assembly as well as in many other manufacturing industrial operations. The Ford motor company estimates that nearly 75% of all power hand tools used corporation-wide are nutrunners. These tools are available from a number of production hand tool manufacturers in a variety of handle configurations and sizes with respect to torque output, spindle diameter, handle length, speed, and weight.

Nutrunners are a concern because of their widespread use in manufacturing and the need for prevention of upper extremity cumulative trauma disorders (CTDs) among workers. Power hand tool operation has been associated with upper extremity CTDs in numerous studies (Rothfleisch and Sherman 1978, Cannon *et al.* 1981, Silverstein *et al.* 1987). Tool and job design factors attributed to the cause, precipitation, and aggravation of these disorders include force, posture, repetitiveness, contact stress, and vibration (Armstrong *et al.* 1986). Forceful exertions can also affect localized muscle fatigue. At present, the best method of preventing CTDs and minimizing the effects of fatigue is by designing tools and jobs that minimize these factors. Although the type of nutrunner considered in this study has not been particularly implicated as causing upper extremity CTDs, it was studied because of the high reaction forces some of these tools are capable of producing.

The most common nutrunner handle configurations are in-line (straight), pistol grip, and right angle. Figure 1 illustrates an operator holding a right angle nutrunner. Right angle nutrunners are most often used for securing fasteners requiring high levels of torque (>20 Nm). Ford design standards classify nutrunners into 27 increasing torque categories ranging from 0·8 Nm to 700 Nm.

Forces acting upon the hand when operating right angle nutrunners include; (1) push force; (2) tool support force; and (3) torque reaction force. Push force is necessary

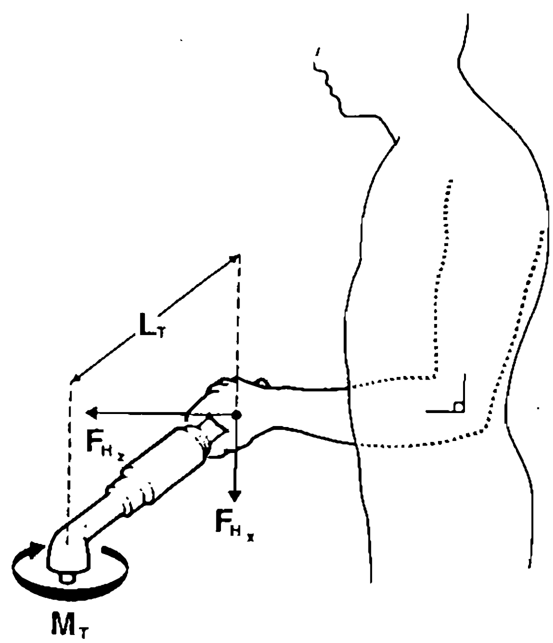

Figure 1. Forces and moments produced during right angle nutrunner operation acting against the hand. The coordinates are based on the International Organization for Standardization (ISO 1984) hand and arm basicentric coordinate system, referenced with respect to the handle and hand.

for starting a fastener and keeping the bit or socket engaged during the securing cycle, and is affected by the work material and design of the fastener. The force necessary for supporting the tool is dependent upon the tool weight, its centre of gravity, the length of the tool, and air hose attachments. Torque reaction force is produced by spindle rotation and is affected primarily by the spindle torque output and tool length. Grip force is the tool operators' reaction opposing these forces for supporting the tool and preventing it from losing control.

Right angle nutrunner operation often requires using both hands, especially for operating the larger tools, however only one hand usually is affected by torque reaction force. The hand holding the distal handle is used for reacting against the torque reaction force and providing tool support force while the other hand produces push force. This study considers only the support and torque reaction force components at the nutrunner handle.

The three major operating modes for nutrunners are either *mechanical clutch*, *stall*, or *air sensing shut-off*. Although clutch tools limit operator reaction force exposure, ratcheting clutch tools can expose workers to significant levels of vibration (Radwin and Armstrong 1985). This method of limiting torque reaction force is undesirable since hand tool vibration has been associated with upper extremity cumulative trauma disorders (Rothfleisch and Sherman 1978, Cannon *et al.* 1981, Armstrong *et al.* 1987). In addition some types of clutch tools produce less desirable performance characteristics than stall or shut-off nutrunners.

Torque reaction time is defined as the total torque build-up time and the time until the tool completely shuts off. When a stall tool is used, exposure to maximum reaction force is directly under operator control by releasing the trigger, which can last as long as several seconds. Stall tools, therefore, tend to have the longest torque reaction times and subject an operator to the longest exposure to torque reaction force. The speed of the air shut-off mechanism controls exposure to peak torque reaction force for shut-off tools. Consequently air shut-off tools have the shortest torque reaction time since these tools cease operating immediately following torque build-up after the desired peak torque is achieved. Typically a shut-off tool takes 8 ms to 75 ms to shut-off limiting a worker's exposure to the peak torque reaction force. However, torque build-up times for both stall and shut-off tools are similar.

Torque reaction forces at the hands and arms of power screwdriver operators were studied by Stevenson and Baidya (1984). They found that under static conditions the torque sustained by the wrist and arm for preventing in-line powered screwdrivers from rotating was the same as if non-powered tools were used. Stevenson and Baidya observed that the final tightening and its reaction occurred more *sharply* with power screwdrivers than if manual tightening were used. They did not indicate, however, the undesirable effects of the sharp reaction force transmitted to the hand. Right angle nutrunners use the mechanical advantage provided by the long handle for limiting torque reaction force transmitted to the operator's hand.

The neuromuscular effects of power tools have been considered previously by Carlsöö and Mayr (1974) who found that pneumatic hammer recoil produced a stretch reflex and muscular contractions in the elbow and wrist flexors. They suggested that repetitive stretching of muscle attachments from these reflexes can cause pain and lead to morphological changes. Radwin *et al.* (1987) found hand tool operation can introduce disturbances in muscle control which can result in excessive grip exertions. Muscles exposed to hand tool vibration can react by exhibiting a tonic vibration reflex in the form of an increasing involuntary contraction. The magnitude of this increase was on the same order as a two-fold increase in load weight, where average grip force increased 56%. It was concluded that this effect was due to the tonic vibration reflex which is mediated through muscle spindles.

Muscle spindle response to rapid stretch is well known (Bianconi and Van Der Meulen 1962). Studies on de-efferented animal preparations have demonstrated that both primary and secondary muscle spindle endings are more responsive to increasing velocity of stretching (Matthews 1963). The effects of sinusoidal and trapezoidal varying forces applied to muscle were investigated in humans by Berthoz and Metral (1970) and others (Neilson 1972, Agarwal and Gottlieb 1977, Zahalak and Heyman 1979, Cannon and Zahalak 1982, Dagalakis *et al.* 1987) who studied the frequency response characteristics of tonic stretch reflexes and demonstrated active muscle responses to external force disturbances.

This investigation studies the effects of right angle nutrunner operation on extrinsic hand flexor and extensor muscles in the forearm. It was hypothesized that either increasing spindle torque or shortening torque reaction time will affect extrinsic hand muscle contraction, and hence grip exertions, through a reflex response. The independent variables included peak spindle torque, and torque reaction time. These variables were of particular interest since they are often directly under the control of engineers specifying, selecting, and designing power hand tools.

2. Methods

2.1. *Mechanical models*

Figure 1 illustrates a free body diagram of a worker holding a right angle nutrunner and the associated forces acting against the hand and arm. Since the spindle acts as a fulcrum, the vertical support force (F_{H_X}) acting against the hand can be determined from the tool weight (W_T), the length between the centre of the nutrunner spindle and the centre of the tool handle (L_T), and the distance between the centre of the spindle and tool centre of gravity (L_{TCG}), such that:

$$F_{H_X} = \frac{W_T L_{TCG}}{L_T} \tag{1}$$

The weight of the air hose and its coupling is not introduced to simplify this model since its effect depends upon the particular installation, however the air-hose also contributes to the vertical support force. The effect of the air hose will be considered later.

Torque reaction force is due to the spindle torque (M_T) and the tool handle length (L_T). The reaction force component (F_{H_Z}) acting against the hand can be determined using the ratio of the torque produced at the tool spindle and the handle length using the equation:

$$F_{H_Z} = \frac{M_T}{L_T} \tag{2}$$

The magnitude of the resultant force acting against the hand ($|F_{HAND}|$) is computed using:

$$|F_{HAND}| = \sqrt{F_{H_X}^2 + F_{H_Y}^2 + F_{H_Z}^2} \tag{3}$$

Substituting equations (1) and (2) into equation (3), and assuming the horizontal component (F_{H_Y}) is negligible, the resultant force magnitude is therefore described as:

$$|F_{\mathrm{HAND}}| = \frac{\sqrt{(W_T L_{TCG})^2 + M_T^2}}{L_T} \tag{4}$$

and the resultant hand force angle α:

$$\alpha = \tan^{-1} \frac{W_T L_{TCG}}{M_T} \tag{5}$$

As torque is applied to a fastener, the fastener rotates at a relatively low spindle torque until the clamped pieces come into intimate contact. This value can approach zero with free running nuts or can be rather significant as in the case where locking nuts, thread interference bolts, or thread forming type fasteners are used. The time that the fastener rotates freely is called the *run-down time.*

After the fastener brings the clamped members of the joint into initial intimate contact it continues to draw the parts together until they form a solid joint. When the joint becomes solid, continued turning of the nut results in a proportionally increasing torque. This is the elastic portion of the cycle and is the time when torque reaction forces are produced. The torque build-up function plotted against time resembles a ramp function (see figure 2). Torque build-up, and consequently torque reaction force, continues rising at a fixed linear rate until peak torque is achieved, which is the clamping force of the joint.

Joint stiffness ranges from hard to soft. Hard joints are formed when bringing two solid objects together. Soft joints involve two objects having more elastic properties. *Torque Rate* is often used for measuring joint stiffness and is defined as the angular rate of torque build-up to the resistance of tightening. It is measured using spindle torque versus spindle rotation, in units of Nm per revolution. For example the same nutrunner can be used in a hard joint such as attaching a pulley to a crankshaft at a torque rate of 600 Nm/rev, or in a soft joint such as a body mount at a torque rate of 6 Nm/rev. Torque build-up typically ranges between 0·5 s for a hard joint to 2 s for a soft joint (see figure 2).

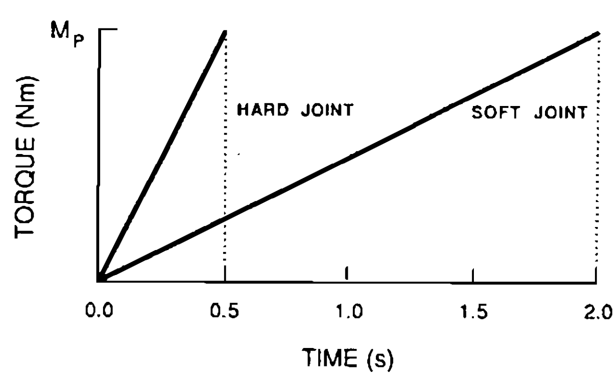

Figure 2. Template for spindle torque output during torque build-up phase. Torque build-up time for both soft joints and hard joints are illustrated. M_p is the peak spindle torque which is the desired torque output and is independent of joint stiffness.

2.2. *Equipment and experimental apparatus*

Four tools were used for this study. Each tool was a right angle nutrunner from the same manufacturer having similar design and handle configurations. All were pneumatic torque shut-off tools operating at 6·3 kg/cm^2 air pressure. Table 1 lists the dimensions, weight, speed, and recommended torque range for each tool. The tools represented an increasing range of right angle nutrunner torque outputs between 30 Nm and 100 Nm and were respectively assigned increasing identification numbers 1 to 4 based on increasing peak spindle torque. The tool having largest torque output, tool 4, represented the largest tool typically used without providing a torque reaction device.

The handle diameter for all the tools was 3·3 cm. The tools were activated by squeezing a lever located at the tool handle. The trigger activation compression force was measured as 20 N using a Chattilon spring scale. No gloves were worn while using the tools in this experiment.

The tools were operated using a GSE (Farmington Hills, MI) model 567M specially modified pneumatic tool test stand for simulating free run and final pull-up phases of securing a threaded fastener. The right angle nutrunner socket was coupled to a spindle attached to a pneumatic brake. Activating the brake provided the resistance for simulating the elastic portion of fastener tightening. A GSE model 2050 rotating socket wrench torque transducer with a GSE model 228-D torque meter measured the torque produced by the tool at the spindle. The spindle and brake system eliminated the need for using fasteners while operating the tool and minimized push force, thereby providing a repeatable task for this study. To account for the loading of the air hose and associated coupling hardware, vertical support force at the tool handle was directly measured using a Chattilon spring scale.

Joint hardness was simulated by controlling air pressure and flow to the pneumatic brake of the power tool test analyser. A torque reaction time of 2 s was defined as a soft joint and a 0·5 s torque reaction time was used for the hard joint. These particular torque reaction characteristics were selected because all the tools tested were capable of performing within this range.

The nutrunners were operated using the right hand for holding the tool handle. The left hand palm was permitted for stabilizing the nutrunner head at the spindle and preventing the tool from slipping off the socket, which is the usual posture assumed when using right angle nutrunners, however the push force was not considered. The elbow angle was fixed at a 90° included angle (see figure 1). To maintain this posture,

Table 1. Specifications of right angle nutrunners.

Tool	Length[1] (cm)	Weight[2] (kg)	Speed (rpm)	Mean torque adjustment range (Nm): 3·9 kg/cm^2 Air pressure	Mean torque adjustment range (Nm): 5·9 kg/cm^2 Air pressure
1	34	2·15	725	20	25
2	37	2·38	390	30	40
3	39	2·49	460	40	55
4	50	2·60	280	70	90

Notes: [1] Handle length measured from spindle centre to centre of the tool handle.
[2] Weight without air hose, associated coupling hardware, or socket.

subjects were raised using an adjustable platform until the tool handle was at elbow height and the desired elbow posture was achieved.

Surface electromyograms (EMGs) were recorded from the anterior and posterior sides of the right forearm. Bipolar, silver–silver chloride Hewlett Packard model 14240A electrodes were positioned to measure EMGs from extensor and flexor muscles of the hand and wrist. Palpation for the flexor palmaris longus and carpi radialis for flexor muscles and extensor digitorum communis for extensor muscles determined placement. Electromyograms were measured differentially with respect to a reference ground electrode. The EMG signals were rectified and passed through an rms converter having a time constant of 200 ms.

The EMG signals and torque meter outputs were digitized using a 12-bit analog-digital converter, at a sample rate of 100 points per second. The converter was operated using a microcomputer and the data were stored on diskettes for later analysis.

2.3. *Subjects*

Five subjects participated in the study. One subject was female and four were male. A summary of subject data is included in table 2. The level of experience each subject had operating pneumatic power tools and nutrunners varied ranging from no prior experience for Subject 1, to more than 30 years of experience for Subject 4. All subjects described themselves as right handed individuals. Subjects gave informed consent and their participation was voluntary.

The subjects were administered a grip and pull strength test prior to the experiment using the right hand. Grip strength during a maximal static power grip exertion with a pronated wrist was measured using a strain gauge dynamometer for measuring the peak compression force between two bars separated a span of 3 cm. This span was used to approximate the grip diameter of the tool handles. Two repetitions were made and the largest peak force attained was taken as the subject's grip strength. The pull strength test was similarly administered having the subjects pull a handle horizontally with the elbow at a 90° included angle and the hand pronated in the same posture used to operate the nutrunners. Subject strength measurements are included in table 2.

2.4. *Experimental design and procedures*

Independent variables included four tools having increasing torque output operating at two torque reaction times. These conditions were presented randomly to each subject. Three repetitions were used for each condition and averaged. Subjects received a 5 min rest in between experimental conditions.

Forearm flexor rms EMG signals were used to estimate grip exertions (Bouisset *et al.* 1973, Armstrong *et al.* 1979). Force calibration was preformed both prior to the actual experiment and following the experimental session and was pooled. Four

Table 2. Summary of subject data.

Subject	Sex	Age (yr)	Body weight (kg)	Stature (cm)	Grip strength (N)	Pull strength (N)
1	F	25	66	172	196	88
2	M	25	75	178	432	373
3	M	34	95	173	746	275
4	M	57	84	170	589	314
5	M	44	82	170	412	196

exertion levels, lasting 4 s each, were used for each calibration. Exertion levels were set for equal divisions up to 50% of each subjects grip strength. Subjects gripped the dynamometer handle using sufficient exertions to centre a beam on a cathode ray tube display indicating the required grip force. Calibration lines using linear regression through the origin were produced for each subject using the average rms EMG as the independent variable and the force levels as the dependent variable. Coefficients of determination for force calibration regression lines ranged between 0·95 and 0·98.

2.5. *Data analysis*

The nutrunner operation cycle was divided into three phases. These included; (1) Pre-start phase; (2) Run-down phase; (3) Torque-reaction phase; and (4) Post Shut-off phase. The phases were identified based on the spindle torque output. Figure 3 shows a representative spindle torque output plotted against time. The Pre-start phase is the time when the tool is held in the operating position but prior to trigger activation. The Run-down phase begins when the operator squeezes the tool trigger producing a small brief spike on the torque output signal. The Torque-reaction phase begins when the torque starts to rise at a constant rate. The Post shut-off phase begins when the torque output returns to zero after peak torque is achieved and the shut-off mechanism is activated.

Flexor rms EMG signals were scaled according to the force calibration regression coefficients for each subject. Peak and average rms EMG levels were obtained for each phase of the nutrunner operation cycle using the torque record for identifying the respective phase. Flexor rms EMG records were also integrated during the Torque-reaction phase to estimate grip force impulse. Flexor rms EMG data, scaled for grip force, was analysed using the regression approach to analysis of variance (ANOVA) for a repeated measures experimental design where subjects served as random effect blocking variables.

3. Results

The average peak torque measured for each tool is included in table 3. These data were used for computing peak resultant hand force based on torque reaction force using equation (2) and the vertical force measured at the handle (see table 3). The peak horizontal torque reaction force (F_{HZ}) was the largest component for all the tools accounting for 97·7% to 99·5% of the peak resultant hand force. Peak horizontal torque reaction force at the handle more than doubled from 87 N to 201 N between the smallest size tool (Tool 1) and the largest size tool (Tool 4) while the vertical force measured at the handle increased less than 25% from 21 N to 26 N. The resultant hand

Table 3. Peak hand forces for right angle nutrunners used in this study.

Tool	Average ± s.d. Peak Torque (Nm)	Peak horizontal force at handle (N)	Vertical force at handle (N)	Resultant hand force Magnitude (N)	Resultant hand force Angle (degrees)
1	29·7 ± 0·8	87	21	89	14
2	46·7 ± 1·6	127	23	129	10
3	58·9 ± 1·0	150	25	152	9
4	99·4 ± 5·5	201	26	202	7

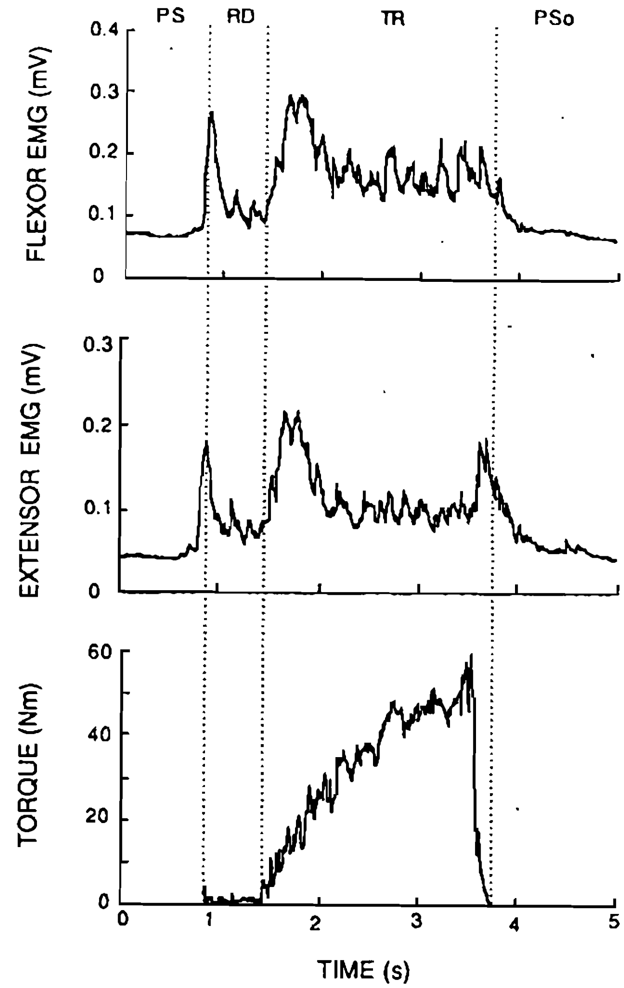

Figure 3. Representative nutrunner spindle torque output and associated forearm flexor and extensor rms EMG response for a 2 s long torque reaction time. The Pre-start phase is indicated by PS, the Run-down phase is indicated by RD, the Torque-reaction phase is indicated by TR, and the Post Shut-off phase is indicated by PSo.

force angle with respect to the horizontal, decreased for tools having increasing peak spindle torque due to the large horizontal torque reaction force component.

Figure 3 and figure 4 show representative flexor and extensor rms EMG records in relation to the nutrunner operation cycle for both long and short torque reaction times. The rms EMG wave form shapes were similar for all subjects and experimental conditions. The torque record determined the actual phase of nutrunner operation. Muscle activity during the Pre-start phase represented the grip force used for holding and stabilizing the tool prior to activating the trigger. When the trigger was squeezed the EMG record rapidly peaked and settled to a steady level of activity for the remainder of the Run-down phase. During the Run-down phase the nutrunner spindle torque was relatively low and remained approximately constant for the entire phase. Run-down lasted for about 0·5 s. The Torque-reaction phase began when spindle torque started to linearly increase. Shortly after the onset of the Torque-reaction phase,

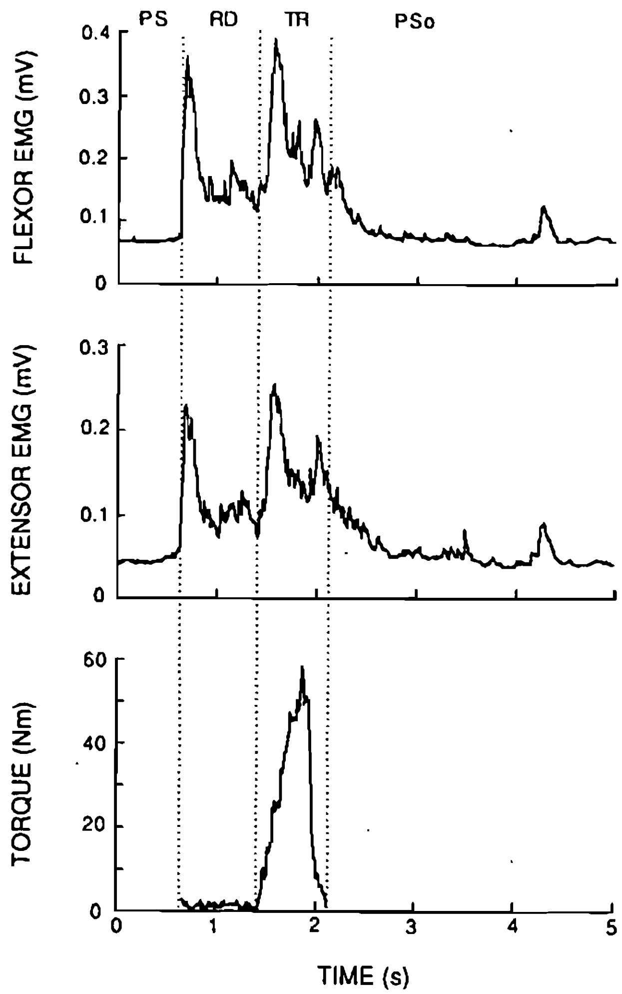

Figure 4. Representative nutrunner spindle torque output and associated forearm flexor and extensor rms EMG response for a 0·5 s short torque reaction time. The Pre-start phase is indicated by PS, the Run-down phase is indicated by RD, the Torque-reaction phase is indicated by TR, and the Post Shut-off phase is indicated by PSo.

both the flexor and extensor EMG records peaked again. Flexor and extensor EMG activity settled to a steady level until the end of the Torque-reaction phase, when peak spindle torque was attained. At this point in the nutrunner operation cycle, the shut-off mechanism was activated causing spindle torque to rapidly approach zero. During spindle shut-off, the extensor EMG, and sometimes the flexor EMG as well, displayed a third peak occurring shortly after shut-off.

Multiple paired comparisons between the average flexor rms EMG, scaled for grip force, during each phase for five subjects are presented in table 4. No significant difference ($p<0{\cdot}95$) was observed between the average flexor muscle activity while holding the tool prior to squeezing the nutrunner trigger during the Pre-start phase (137 ± 42 N) and the average flexor muscle activity during the Post Shut-off phase (138 ± 46 N) after the tool stopped. The greatest average flexor muscle activity (415 ± 170 N) occurred during the Torque-reaction phase when spindle torque

Table 4. Pairwise comparisons between average rms EMG scaled to grip force (N) for each nutrunner phase.

		Phase		
Phase		Run-down	Torque-reaction	Post shut-off
Pre-start	Mean Diff.	−81*	−278**	0
	s.d.	159	147	43
Run-down	Mean Diff.		−198**	80*
	s.d.		261	163
Torque-reaction	Mean Diff.			278**
	s.d.			140

Notes: * $p<0{\cdot}01$
** $p<0{\cdot}001$

increased from zero to maximum and back to zero, where average flexor rms EMG scaled for grip force was more than four times greater than during the Pre-start phase.

Average flexor rms EMG activity, scaled for grip force, during the Pre-start phase increased 26 N from 126 ± 41 N to 152 ± 45 N when increasing tool size from tool 1 to tool 4 for the Tool effect which was marginally significant ($F(3,27)=3{\cdot}16$, $p<0{\cdot}05$). No significant effects were found for the Time effect of torque reaction time ($F(1,27)=0{\cdot}63$, $p<0{\cdot}5$) or the Tool × Time interaction ($F(3,27)=0{\cdot}50$, $p<0{\cdot}7$).

Average flexor rms EMG activity, scaled for grip force, during the Run-down phase of the nutrunner operation cycle is plotted against increasing tool torque output size in figure 5. Average flexor rms EMG activity during the Run-down phase (see figure 5) increased 147 N from 161 ± 90 N to 308 ± 174 N when increasing tool size from the smallest tool tested (Tool 1) to the largest (Tool 4) ($F(3,27)=15{\cdot}10$, $p<0{\cdot}001$). No significant effects were found for the effects of Time ($F(1,27)=0{\cdot}17$, $p<0{\cdot}7$) or Tool × Time interaction ($F(3,27)=0{\cdot}25$, $p<0{\cdot}9$).

Average flexor rms EMG activity, scaled for grip force, during the Torque-reaction phase is plotted versus tool size in figure 5 and plotted against torque reaction time in figure 6. Flexor rms EMG activity during the Torque-reaction phase indicated average grip force increased 77 N from 372 ± 159 N to 449 ± 194 N when increasing tool torque output from the smallest tool (Tool 1) to the largest tool (Tool 4) ($F(3,27)=9{\cdot}52$, $p<0{\cdot}001$). Average flexor rms EMG activity, scaled for grip force, was 50 N greater for the short torque reaction time than the long torque reaction time, increasing from 390 ±159 N to 440 ± 180 N ($F(1,27)=26{\cdot}66$, $p<0{\cdot}001$). However no significant effect was indicated for the interaction between Tool × Time ($F(3,27)=0{\cdot}96$, $p<0{\cdot}5$).

Although average flexor rms EMG activity during the Torque-reaction phase was greater for short torque reaction times than long torque reaction times, integrated grip force impulse estimated using flexor rms EMG scaled for grip force and integrating over the Torque-reaction phase was 527 Ns less for short torque reaction times than for long torque reaction times, decreasing from 839 ± 362 Ns to 312 ± 132 Ns ($F(1,27)=128{\cdot}08$, $p<0{\cdot}001$). Average grip force impulse is plotted against torque reaction time in figure 7.

Peak flexor rms EMG during the Torque-reaction phase, scaled for grip force, was 26 N greater for short torque reaction times than for long torque reaction times ($F(1,21)=2{\cdot}92$, $p<0{\cdot}1$), however this measurement should be discounted since it sometimes exceeded the limits of the grip force calibration regression range and its

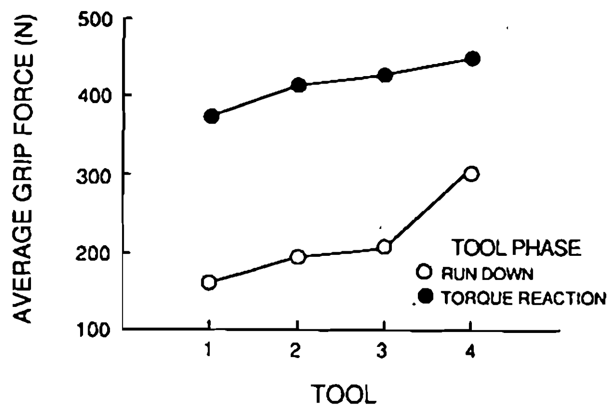

Figure 5. Average grip force vs. Tool for the Run-down and Torque Reaction phases (five subjects).

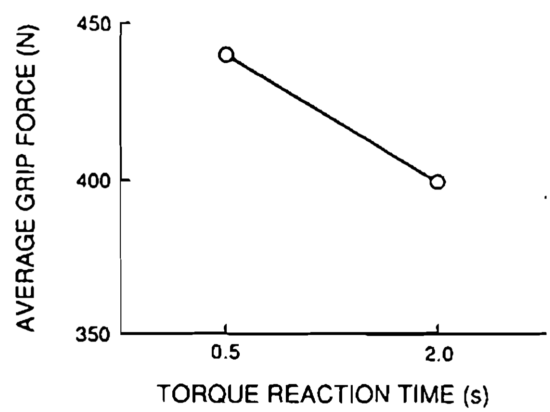

Figure 6. Average grip forces during the Torque Reaction phase for long and short torque reaction times (five subjects).

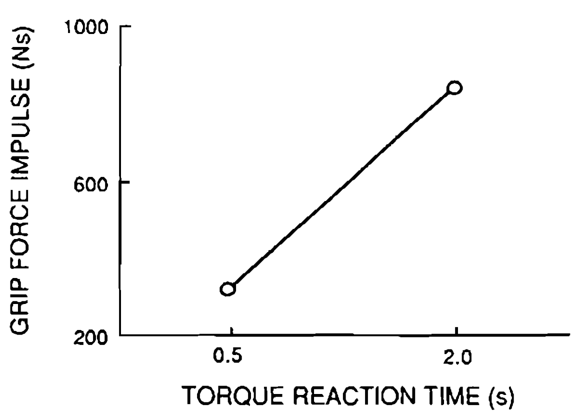

Figure 7. Average grip force impulse during the Torque Reaction phase derived from integrating rms EMG records scaled for grip force, for long and short torque reaction times (five subjects).

significance level was marginal. No significant effects were found for Tool ($F(3,21) = 1{\cdot}27$, $p < 0{\cdot}3$) or Tool × Time ($F(3,21) = 0{\cdot}18$, $p < 0{\cdot}9$).

Post-shut-off flexor rms EMG activity was statistically significant ($F(1,27) = 15{\cdot}23$. $p < 0{\cdot}001$) for the Time effect, resulting in 26 N less average grip force following short torque reaction times than following long torque reaction times, however the effect was relatively small. No significant effects were found for the Tool effect ($F(3,27) = 0{\cdot}25$, $p < 0{\cdot}9$) or the Tool × Time interaction ($F(3,27) = 1{\cdot}33$, $p < 0{\cdot}3$).

The average latency between tool spindle torque onset, at the start of the Torque-reaction phase, and peak flexor rms EMG was 294 ± 133 ms for long torque reaction times and decreased to 161 ± 76 ms for short torque reaction times. This was significant ($F(1,24) = 17{\cdot}68$, $p < 0{\cdot}001$) after applying a square root transformation for stabilizing variances. No significant effects were observed for the extensor response following onset of spindle torque.

The average latency between peak tool spindle torque, just prior to tool shut-off, and peak flexor rms EMG was 97 ± 83 ms for long torque reaction times and decreased to 47 ± 67 ms for short torque reaction times. The average shut-off latency between peak tool spindle torque and peak extensor rms EMG for long torque reaction times was 188 ± 50 ms and decreased to 116 ± 46 ms for short torque reaction times. The effect of torque reaction time on the shut-off latency was significant for both for flexor muscles ($F(1,27) = 7{\cdot}78$, $p < 0{\cdot}01$) and extensor muscles ($F(1,27) = 19{\cdot}17$, $p < 0{\cdot}001$).

Grip force differences among subjects was considerable. Average flexor rms EMG differed as much as 148% between subjects. The effect of Subjects was significant ($p < 0{\cdot}001$) for all analysis of variance tests except for extensor latency data where no significant Subject effect ($p < 0{\cdot}65$) was found.

Multiple regression analysis, based on the ANOVA results, was used to model average grip force exerted during the Torque-reaction phase for the effects of hand force (F_H) and torque reaction time (T). Hand force was determined using equation (4). A model for grip force population means exerted during the Torque-reaction phase was computed and the results are presented in figure 8.

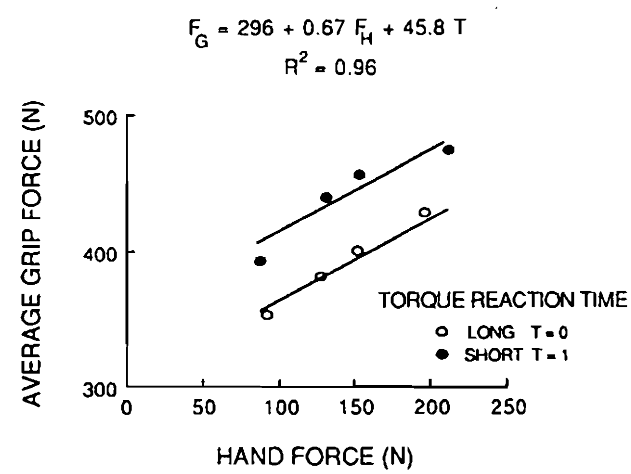

Figure 8. Average grip force (F_G) during the Torque Reaction phase for both short and long torque reaction times plotted against average peak hand force (F_H) for five subjects. Regression lines are included. The indicator variable (T) was equal to zero for the long torque reaction time and equal to one for the short torque reaction time condition.

The average static pull strength measured for the five subjects participating in this study was 249 ± 110 N. Table 3 indicates that torque reaction force was 35% of the average pull strength for tool 1, 51% of the average pull strength for tool 2, 60% of the average pull strength for tool 3 and 81% of the average pull strength for tool 4. Furthermore torque reaction force exceeded the static pull strength of subject 1 using tools 2, 3 and 4, and exceeded the static pull strength of subject 4 using tool 4 (see table 2).

4. Discussion

Muscle activity during the Pre-start and Post shut-off phases was indicative of grip exertions used to support the stationary hand tool. Forearm muscle activity after the trigger was activated, initiating the Run-down phase, represented grip force used to counteract reaction forces produced during free spindle rotation. The torque reaction force during the Run-down phase was relatively low and torque reaction force during the Run-down was a function of the inertial effects of the rotating spindle. Grip exertions during the Torque-reaction phase increased dramatically. Increasing torque reaction force during the Run-down phase should increase the tool operation force requirements. Torque reaction force during the Run-down phase can increase for instance, when using self tapping or drill-point fasteners, or when drilled and tapped hole sizes are improper size.

Torque reaction force was by far the greatest force component acting against the hand. The torque reaction force component at the handle (F_{Hz}) was four times greater than the vertical support force (F_{Hx}) acting against gravity for the smallest tool, 1, and was as much as eight times greater than the vertical support force for the largest tool, 4. The significance of torque reaction force was demonstrated by the Torque-reaction phase having the greatest forearm muscle response (see table 4).

If the magnitude of the vertical support force (F_{Hx}) acting against the hand is small with respect to torque reaction force (F_{Hz}), equation (4) indicates that the hand force is directly proportional to spindle torque. Since peak spindle torque specifications are determined from engineering requirements, lowering peak spindle torque for controlling hand forces is not usually feasible. Equation (4) furthermore reveals that hand force is inversely proportional to the tool length. The general practice therefore, has been to lengthen the tool. Although the handle length of the nutrunners studied increased for increasing spindle torque output (see table 1), the resultant hand force magnitude still increased indicating that the tool length designs were not long enough to account for the increased spindle torque output. It is recommended that the tool handle length should compensate for the increased spindle torque, maintaining equivalent torque reaction forces to the hand for all right angle nutrunners, however this was not the case for the tools studied.

Production power hand tools are often constructed from aluminium to minimize their weight. After weighing an aluminium nutrunner housing tube and drive shaft it was determined that extending a right angle nutrunner will add 0·04 kg to the total tool weight for each cm extended. For example, from equation (2) it was estimated that increasing the largest nutrunner handle length, tool 4, by 25 cm would decrease the peak torque reaction force from 201 N to 133 N. The total tool weight would only increase by 1·0 kg for a total weight of 3·6 kg. Assuming a proportional shift in the centre of gravity due to the increased weight at the tool handle, and ignoring the effect of the air-hose, the resultant hand force would still decrease 33% from 202 N to 135 N. This reduction in hand force would be close to the hand force determined for tool 2.

Hence, further increasing the handle lengths would be beneficial for lowering hand force in relation to torque reaction. However there is a limit to the length that a tool can be extended before it becomes too cumbersome to hold and manipulate.

Alternative methods for limiting torque reaction force include; (1) use of torque reaction bars; (2) installing torque absorbing suspension balancers; (3) providing tool mounted nut holding devices; and (4) installing tool support and reaction arms. Tools can be equipped with a stationary reaction bar adapted to a specific operation so the reaction forces can be absorbed by any convenient solid support. Stall bars can be installed on pistol grip, in-line, and right angle tools. Advantages of tool mounted reaction devices include; (1) all reaction forces are removed from the operator; (2) one hand operated pistol grip and in-line reaction bar tools can be used rather than right angle nutrunners that usually require two hands; (3) reaction bar tools can be less restricting on the operator's posture; (4) tool speed and weight improvements over right angle nutrunners in most tool sizes; and (5) use of reaction bars can improve tool performance. The disadvantages are that reaction bars must be custom made for each operation and the combination of several attachments for one tool can be difficult. Torque reaction bars also add weight to the tool and can make the tool more cumbersome to handle. Although reaction devices on right angle tools can increase their weight, it may be a desirable trade-off for reducing high reaction forces.

Providing tools with torque reaction bars or using torque absorbing suspension systems can eliminate torque reaction effects completely, although these interventions are not always practical, especially when there is limited accessibility, manipulation restrictions, or no surface for a reaction bar to contact. However, a shorter tool can be used if a reaction bar is provided. Acceptance and use of these devices varies greatly.

Overhead torque reaction and suspension devices are best suited for assembly operations that can use a spring balancer or air balancer. Floor or side mounted articulating reaction and support devices are also available and the development of these devices has progressed rapidly in the last few years. Articulating arms help support the tool weight, absorb torque reaction forces, and free the hands for other activities. However, articulating arms restrict freedom of motion and may require an operator to manipulate a greater mass.

The weight of the air hose was measured at the handle to account for its contribution when determining the hand force. The contribution of the air hose to the vertical force (F_{H_X}) at the hand was not included in the model presented in equation (1), and its effect was considered the same for every tool for comparison purposes, however it can be approximated as a directly additive effect. The air-hose weight contribution to F_{H_X} was included in the analyses for this study using direct measurements. The effect of the air hose can be minimized by using the lightest weight air hose and associated couplings available and making sure the air hose does not interfere with the operator.

Shoulder moments were computed based on the computed resultant hand forces in the sagital plane (see table 3) using static coplanar analysis of upper-arm and forearm segments and applying joint moment–strength mean prediction equations (Schanne 1972) corrected for population strengths of industrial workers performing static exertions (Stobbe 1982), as described in Chaffin and Andersson (1984). For males having 95 percentile stature (188 cm, 99 kg), 99% were predicted capable of the static shoulder strength required for tool 1, 98% for tool 2, 97% for tool 3, and 91% for tool 4. However, for females having 95 percentile stature (173 cm, 91 kg) 95% are predicted capable of producing the shoulder strength required for tool 1, 85% for tool 2, 76% for tool 3, and only 46% for tool 4. Therefore torque reaction force reduction may have a positive effect upon workers' ability to maintain control of right angle nutrunners, especially for individuals having low shoulder strength.

The results of this study agreed with the findings of Berthoz and Metral (1970) who applied linearly increasing force ramps to the forearm. Trapezoidal varying forces were generated using an electromagnetic clutch, having peak amplitudes of 20 N and rise times between 500 ms to 20 ms. They found that when the rise time was greater than 300 ms, the EMG of forearm flexors (biceps, brachii, brachoradialis) showed a brief initial burst of activity. However, when the rise time was shorter than 300 ms a greater EMG burst was recorded. If the rise time was maintained constant and the final force level increased from 10 N to 30 N, the speed of onset increased. When the force input was held at 20 N and suddenly released, EMG activity of the flexors was interrupted and an antagonist burst occurred in the extensors, particularly with rapid fall times. This is also in agreement to what occurred in this study with extrinsic hand muscles of the forearm. The rapid tool shut-off constituted a quick-release response by the antagonist extensor muscles.

The average measured torque reaction time over all experimental conditions for short torque reaction times was actually $0{\cdot}70 \pm 0{\cdot}08$ s and the average torque reaction time for long torque reaction times was $2{\cdot}13 \pm 0{\cdot}33$ s. Hard joint torque reaction times were selected as 0·5 s in this study because it was the shortest torque reaction time that all four tools were capable of operating. Although the 0·5 s hard joint torque reaction time was not actually attained, the 0·2 s error was consistent throughout the experiment. It would be expected, based on Berthoz and Metral (1970), that the increase in grip force for faster torque reaction times could be even greater than the increases found here. Muscle responses for even faster torque build-up times will be investigated in future studies.

Torque reaction time as defined in this study is the sum of torque build-up and torque shut-off times. Torque build-up time, which occupies the largest component of torque reaction time, can be determined using the following relationship:

$$\text{Torque build-up time} = \frac{\text{Peak Torque}}{\text{Spindle Speed} \times \text{Torque Rate}} \quad (6)$$

Since reducing peak spindle torque is usually not feasible and torque rate is determined by the physical characteristics of the material being fastened together, torque build-up time can be increased by reducing spindle rotation speed. Equation (6) also indicates that torque build-up time is shorter for hard joints than soft joints. Hence, lower tool speeds should be considered for effectively providing a softer joint and longer torque reaction times for lowering average grip force during the Torque-reaction phase, especially for hard joints.

Alternately, longer torque reaction time means increased exposure to torque reaction forces. The average integrated grip force response measured during the Torque-reaction phase was only 2·7 times greater for long torque reaction times than for short torque reaction times although the area under the torque reaction force stimulus was four times greater for long torque reaction times than for short torque reaction times. Reducing torque reaction time may decrease operator exposure to torque reaction force, but in light of the results of this investigation it appears that simply reducing torque reaction time by reducing torque build-up time can have an undesirable influence on grip exertions due to reflexive responses of the muscle. The actual trade-off between reducing average grip force and increasing integrated grip force impulse is yet to be determined.

The tendency has been among production engineers towards selecting tools having the greatest speeds, and hence the shortest torque reaction times, in order to enhance productivity. Although increasing tool speed in order to increase the number of fasteners that an operator can install will decrease exposure time to torque reaction force for each individual fastener, it may not at all decrease the total daily exposure to reaction forces if the production standard is increased. Furthermore, the results of this study indicate that increasing tool speed may undesirably increase muscle contraction associated with each fastener. Engineers should therefore use caution when considering increasing spindle rotation speed.

5. Summary

1. Peak torque reaction force was the greatest component of the reaction force acting against the hand, accounting for more than 97% of the peak resultant hand force. Peak hand force increased with increasing tool output capacity indicating that the tool lengths were not long enough for counteracting the increased spindle torque.

2. Forearm muscle rms EMGs, scaled for grip force, indicated average flexor activity during the Torque-reaction phase was more than four times greater than during the Pre-start and Post shut-off phases, and two times greater than during the Run-down phase. Therefore hand forces during the Torque-reaction phase were the greatest concern.

3. Flexor rms EMG activity averaged during the Torque-reaction phase and scaled for grip force increased for increasing tool spindle torque from 372 N for a 30 Nm nutrunner to 449 N for a 100 Nm nutrunner, and was 50 N greater for short torque reaction times than for long torque reaction times.

4. The average latency between tool spindle torque onset and peak flexor rms EMG for long torque reaction times was 294 ms which decreased to 161 ms for short torque reaction times. The average latency between peak tool spindle torque, just prior to tool shut-off, and peak rms EMG after for long torque reaction times was 97 ms for flexors and 188 ms for extensors, which decreased for short torque reaction times to 47 ms for flexors and 116 ms for extensors.

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On a utilisé l'électromyographie de surface pour étudier les effets de la force de torsion de la main sur l'activité musculaire de l'avant-bras et la force de poigne chez cinq sujets utilisant une visseuse d'écrous pneumatique. Quatre outils ayant des broches de torsion croissantes ont été utilisés, avec des temps de réaction courts et longs. Les moments de tornsion variaient entre 30 Nm et 100 Nm. Les temps de réaction courts étaient de 0,50 s et les longs de 2 s. La force horizontale de crête était la composante la plus importante de la force de réaction contre la main et expliquait plus de 97% de la force résultante manuelle. Cette force variait entre 89 N pour l'outil le plus petit et 202 N pour l'outil le plus grand. L'EMG des muscles de l'avant-bras pour la poigne, montre que l'activité des fléchisseurs durant la phase de contre-réaction est quatre fois plus important que durant la phase avant la marche et après l'arrêt et deux fois plus grande que durant le vissage. L'activité EMG des fléchisseurs augmentait en fonction des moments de torsion. On a également observé un accroissement dans l'activité EMG de 372 N pour la visseuse de 30 Nm et de 449 N pour la visseuse de 100 Nm. D'autres variations importantes ont également été trouvées avec cest

outils. Ces résultats montrent que les forces de réaction et de contre-réaction de ce type d'outils peuvent fortement affecter la musculature de la main et de l'avant-bras et donc la force avec laquelle ces outils sont utilisés et où interviennent souvent des réponses réflexes de la main. On peut tenir compte de ces effets en concevant des outils tenus à la main, de manière à minimiser les forces de torsion réactive qui sont transmises à la main; par exemple en utilisant des aides mécaniques, telles que l'allongement des poignées, des barres de torsion ou des systèmes de suspension amortissant les moments de torsion. On peut également minimiser la réponse musculaire en réduisant la virtesse de rotation des broches.

Mit Hilfe der Oberflächenelektromyographie wurden die Wirkungen von in die Hand eingeleiteten Drehmomenten auf Unterarmmuskelaktivität und Greifkraft untersucht. Fünf Probanden bedienten in den Versuchen Druckluftschrauber mit Drehmomentbegrenzung und rechtwinkligem Griff. Vier Werkzeuge mit verschiedenen Drehmomenten an der Spindel wurden eingesetzt und zwar bei kurzen und langen Drehmoment-Reaktionszeiten. Die Spindel-Drehmomente lagen zwischen 30 und 100 Nm. Die kurze Reaktionszeit betrug 0,5 s während die lange 2 s betrug. Die maximale Horizontalkraft war die größte Komponente der in die Hand eingeleiteten Reaktionskraft und erreichte mehr als 97% der resultierenden Handkraft. Die maximale Handkraft steigerte sich von 89 N für das kleinste Werkzeug bis auf 202 N für das größte Werkzeug. Der Effektivwert des Unterarmmuskel-EMG, nach der Greifkraft skaliert, zeigte, daß die durchschnittliche Flexor-Aktivität während der Drehmomentreaktionsphase vier mal größer war als in den Phasen vor dem Start und nach dem Auslösen und doppelt so hoch wie in der Laufphase vor dem Auslösen. Die Flexor-Muskelaktivität wahrend der Drehmomentreaktionsphase wurde mit ansteigendem maximalem Spindeldrehmoment größer. Der durchschnittliche Effektivwert des Flexor EMG, nach der Greifkraft skaliert, stieg während der Drehmomentreaktionsphase von 372 N für den 30 Nm-Schrauber bis auf 449 N für den 100 Nm-Schrauber. Nach unterschiedlichen Reaktionszeiten gemittelt ergaben sich 390 N für lange Drehmomentreaktionszeiten und 440 N für kurze Drehmomentreaktionszeiten. Trotzdem betrug das über die Drehmomentreaktionsphase integrierte Flexor-EMG im Mittel 839 Ns für lange Reaktionszeiten und nur 312 Ns für kurze Reaktionszeiten. Die mittlere Verzögerungszeit zwischen Drehmomentanstieg und dem ersten Peak des Effektivwertes Flexor-EMG betrug für lange Reaktionszeiten 294 ms und fiel für kurze Reaktionszeiten aur *161* ms. Die mittlere Verzögerungszeit zwischen dem maximalen Spindeldrehmoment unmittelbar vor dem Auslösen und dem letzten Peak der EMG-Effektivwerte betrug bei langen Reaktionszeiten 97 ms für die Flexoren und 188 ms für die Extensoren. Für kurze Reaktionszeiten sanken die Werte auf 47 ms für die Flexoren und 126 ms für die Extensoren. Die Ergebnisse zeigen, daß Drehmomentreaktionen von Schraubern die Handmuskeln im Unterarm und damit die Greifbeanspruchungen in Art einer Reflex-Antwort beeinflussen können. Diese Wirkungen wären zu kontrollieren, in dem bei den Handwerkzeugen Drehmoment-Reaktionskräfte, die auf die Hand übertragen werden, konstruktiv minimiert werden. So könnten die mechanischen Vorteile genutzt werden, die sich aus größeren Grifflängen, Drehmomentreaktionssperren oder das Drehmoment dämpfende Federungssystem ergeben oder es könnten die Muskelreaktionen auf schnelle Drehmomentänderungen durch Reduzierung der Spindeldrehzahl minimiert werden.

直角空気締切ナットランナを使っている5名の被験者の前腕筋活動と握力に及ぼす手に働くトルク反力の影響を表面筋電図を用いて検討した。スピンドル・トルクの異なる4種類の工具をトルク反応時間を変えて操作した。ナットランナ・スピンドル・トルクは30から100Nmの範囲にあった。短いトルク反応時間は0.5秒、長いトルク反応時間は2秒と考えた。最高水平力は手に働く反力の最大成分で、最高手力の97%以上を占めた。最高手力は最小工具の89Nから最大工具の202Nに増加した。握力の目盛の付いた前腕筋rms EMGによると、トルク反応期の平均屈筋活動は作業前期と締切後期よりも4倍以上、弛緩期よりも2倍以上も高かった。トルク反応期の屈筋EMG活動は工具の最高スピンドル・トルクが増えるにつれて活発になった。握力の目盛の付いている平均屈筋rms EMGはトルク反応期に30Nmナットランナの372Nから100Nm ナットランナの449Nに増大した。トルク反応期に平均化し、握力の目盛の付いた屈筋rms EGN活動は長いトルク反応時間の場合390Nで、短いトルク反応時間の場合440Nに減少した。しかしトルク反応期にわたって積分した屈筋rms EMGは長いトルク反応時間の場合839Nで、短いトルク反応時間の場合440Nに減少した。工具