Muscle response to pneumatic hand tool torque reaction forces

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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

![Diagram](image.png)

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 (Rothfelsisch 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 Carlsson 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 \( F_{Hx} \) 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:

\[
F_{Hx} = \frac{W_T L_{TCG}}{L_T}
\]  

(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 \( F_{Hz} \) 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:

\[
F_{Hz} = \frac{M_T}{L_T}
\]  

(2)

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

\[
|F_{HAND}| = \sqrt{F_{Hx}^2 + F_{Hy}^2 + F_{Hz}^2}
\]  

(3)
Substituting equations (1) and (2) into equation (3), and assuming the horizontal component \( F_{h_2} \) is negligible, the resultant force magnitude is therefore described as:

\[
|F_{\text{HAND}}| = \frac{\sqrt{(W_L L_{TCG})^2 + M_T^2}}{L_T}
\]

(4)

and the resultant hand force angle \( \alpha \):

\[
\alpha = \tan^{-1} \left( \frac{W_L L_{TCG}}{M_T} \right)
\]

(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](image)

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/cm² 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 Chantillon 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 Chantillon 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>
<thead>
<tr>
<th>Tool</th>
<th>Length¹ (cm)</th>
<th>Weight² (kg)</th>
<th>Speed (rpm)</th>
<th>3.9 kg/cm² Air pressure</th>
<th>5.9 kg/cm² Air pressure</th>
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<td>40</td>
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<tr>
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<td>39</td>
<td>2.49</td>
<td>460</td>
<td>40</td>
<td>55</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>2.60</td>
<td>280</td>
<td>70</td>
<td>90</td>
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</tbody>
</table>

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 performed both prior to the actual experiment and following the experimental session and was pooled. Four

<table>
<thead>
<tr>
<th>Subject</th>
<th>Sex</th>
<th>Age (yr)</th>
<th>Body weight (kg)</th>
<th>Stature (cm)</th>
<th>Grip strength (N)</th>
<th>Pull strength (N)</th>
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