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A Field Investigation of Manual Forces Associated With Trigger and Push to Start Electric Screwdrivers

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ABSTRACT

This study investigated manual forces associated with trigger start (TS) and push to start (PTS) activation in-line electric screwdriver designs. The vertically directed axial screwdriver force transmitted with the driver to the fastener and the grip/finger forces on the driver handle were measured from 13 employees in an electronics assembly manufacturing facility. The PTS driver was associated with significantly ($p < .01$) higher axial force than the TS driver at two of the four workstations, where the difference was as high as a 184% increase (36.5 vs. 103.8 N). Total finger force on the screwdriver handle was also higher for the PTS screwdriver ($p < .01$). The PTS screwdriver may reduce instances of fastener head damage ("cam out") by requiring a minimum level of axial force to ensure better contact between the screwdriver bit and the fastener. However, this appears to come at the expense of greater manual forces exerted by the operator. © 2007 Wiley Periodicals, Inc.

1. INTRODUCTION

The importance of hand tool design in reducing user discomfort, biomechanical stresses, and risk for cumulative trauma disorders of the musculoskeletal system has been

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underscored in numerous publications (e.g., Freivalds, 1996; Konz, 1974; Tichauer & Gage, 1977). Based on a large-scale questionnaire, Aghazadeh and Mital (1987) estimated that use of hand tools accounted for 6% of all compensable occupational injuries. Although data from this 1987 study indicated that powered hand tools were associated with fewer injuries than nonpowered hand tools, the percentage of powered hand tool injuries that were attributed to overexertion (28%) was actually slightly higher than that percentage for nonpowered hand tools (25%). Freivalds and Eklund (1993) noted that, by virtue of their externally powered designs, electric and pneumatic hand tools have increased productivity at the expense of shortened cycle times and highly repetitive applications of force with the tool.

Ergonomic studies specific to electrically and pneumatically powered screwdriver and nutrunner designs have investigated the effects of such parameters as pneumatic versus DC electric power source (Potvin, Agnew, & Ver Woert, 2004), cutoff torque (Chang & Wang, 2000; Freivalds & Eklund, 1993; Radwin, VanBergeijk, & Armstrong, 1989), torque profile (Armstrong et al., 1999), handle diameter (Johnson & Childress, 1988), pistol versus in-line handle orientation (Freivalds & Eklund, 1993), tool weight (Johnson & Childress, 1988), and hand/arm support aids (Freund, Takala, & Toivonen, 2000). An important design characteristic of electric and pneumatic screwdrivers that has not been studied as thoroughly is the mode of activation and how this mode of activation affects manual forces associated with use of the tool. There have traditionally been two general designs in terms of mode of activation for electric and pneumatic screwdrivers: trigger start and push to start. The former relies on a trigger that is activated by the index finger or the index and middle fingers in combination. The latter relies on axial force transmitted through the shaft of the tool for activation.

One of the few studies comparing the biomechanical demands of trigger start and push to start screwdriver activation modes was that of Chang and Wang (2001), who measured finger forces and the surface electromyogram (EMG) of the flexor digitorum associated with both types of screwdrivers. The push to start driver required 21.3%, 23.5%, 4.8%, and 10.6% greater middle, ring, small, and total finger forces relative to the trigger driver, whereas the trigger driver was associated with a 2.1% higher index finger force. EMG of the flexor digitorum was 15–20% higher with the push to start driver. Chang and Wang concluded that the trigger start in-line pneumatic screwdriver was preferable to the push to start mode of activation. The explanation for the higher finger forces and flexor EMG for the push to start activation mode was not presented in their study. These variables may have been higher because of some aspect of the handle design or because the axial vertical driver force (thrust force), which was not reported, was higher. Without knowledge of the axial forces applied with the screwdrivers, the differences in total finger force between the modes of activation are difficult to interpret.

Few studies have examined the axial force applied with powered screwdrivers or compared trigger and push to start drivers with respect to this axial driver force. Freund et al. (2000) examined the effects of two ergonomic aids on the manual forces associated with a pneumatic in-line screwdriver. Their measurements included the surface electromyogram and the vertical thrust force (axial driver force) transmitted through the shaft of the driver. They reported mean EMG amplitude for flexor digitorum superficialis, flexor digitorum profundus, extensor carpi radialis, and extensor carpi ulnaris muscle groups during the portion of the signal in which the vertical thrust force exceeded 20 N, but the peak levels of vertical thrust force were not reported. Örtengren, Cederqvist, Lindberg, and Magnusson (1991) measured applied axial driver force associated with a pistol grip

electric screwdriver (finger trigger start activation) and a manual screwdriver. Their results suggested that the screw head design had more influence on axial driver force than the type of screwdriver, with a TORX head resulting in lower axial force than a Phillips head.

The present investigation was motivated by process engineers at an electronics manufacturing and assembly facility questioning which mode of activation (trigger start vs. push to start) was preferable from an ergonomics standpoint. This facility was using both push to start and trigger start screwdrivers for low torque fastener insertion in assembly processes. The purpose of the present study was to compare the trigger and push to start modes of activation in terms of the manual forces exerted by the user in a realistic manufacturing assembly environment. In addition to the measures of finger force reported in previous work, the present study measured the vertically directed axial driver force associated with both modes of activation. Other objectives of the study were to determine whether differences in finger forces between the two modes of activation could be explained based on differences in axial driver force and to characterize the distribution of finger force on the driver as a function of mode of activation.

2. METHOD

2.1. Tools Evaluated

This study was conducted in cooperation with Alpine Electronics of America, Inc. This particular facility used both trigger start and push to start screwdriver designs for the insertion of fasteners in the assembly of electronic components. One screwdriver representative of each mode of activation was selected for the investigation. The trigger start screwdriver, which is activated by a finger trigger (see Figure 1a), was the HIOS model
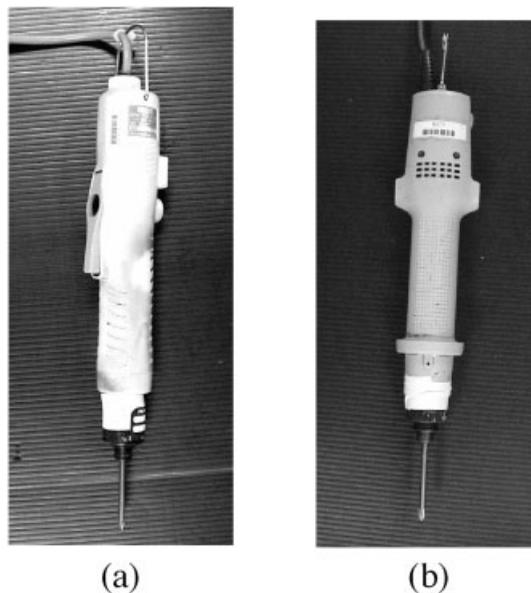

(a)   (b)

Figure 1   Trigger start driver (a) and push to start driver (b) evaluated in the study. For more details see text.

VZ-1820. This was a paddle trigger that could be used by one or more fingers. The push to start screwdriver, which is activated by the axial driver force directed against the head of the fastener (see Figure 1b), was the Aimco model AE-1411. The weight of the HIOS VZ-1820 is listed as 0.680 kg by its manufacturer; the weight of the Aimco AE-1411 is listed as 0.724 by its manufacturer. It is important to note that the screwdrivers were suspended with tool balancers so that the mass of the tools was not supported by the worker during use of the tools. Both screwdrivers were in-line designs with cylindrical grip surfaces of 38 mm (HIOS VZ-1820) and 39 mm (Aimco AE-1411) diameter. Identical Phillips head bits were used with both screwdrivers. The in-line design requires grip force to create a vertically directed axial force necessary to firmly seat the bit within the head of the screw. Figure 2 depicts the manual forces involved. The cutoff torque settings were between 0.57 and 0.78 N·m depending on the particular workstation. The screwdrivers were set to have the same cutoff torque within each workstation.

Four workstations were chosen in which to evaluate the two screwdriver designs in assembly work. These four workstations were designated AS2, OP2, Main Assembly 1, and Main Assembly 2. The criteria used to select these workstations were that multiple employees were trained at the particular process at each of these workstations and that the force sensing platform (described below) could be placed between the work surface and the work holding fixture without compromising the quality of the product. Differences in the workstation layouts were believed to be less influential on the manual force exertion with the screwdrivers than were the properties of the product component and the fasteners that were inserted at the workstation.

2.2. Participants

A total of 13 employees from the Alpine Electronics facility participated in the study. Their participation was voluntary and took place during their normal work shift without

Figure 2   Representation of manual forces measured on the in-line screwdrivers (FF: finger force, AF: axial force).

TABLE 1.   Study Participants and Assignment to Workstation

Subject	Gender	Age	Years experience[a]	Workstation(s) tested			
1	f	41	12	AS2	OP2		
2	f	42	12	AS2			
3	f	46	3			MA1	
4	f	44	12				MA2
5	m	40	15	AS2	OP2		
6	f	44	15			MA1	MA2
7	f	21	0.75		OP2		
8	f	45	14			MA1	
9	f	39	16			MA1	MA2
10	f	47	15				MA2
11	f	39	17			MA1	MA2
12	m	25	0.2		OP2		
13	f	45	16			MA1	MA2
Mean		39.8	11.4				
SD		8.0	6.0				

[a]Years experience refers to the duration of time working at this facility.

compensation beyond their normal hourly wage. Participants provided informed consent to participate in the study and the study protocol was approved by the Human Subjects Review Board at the National Institute for Occupational Safety and Health. Six of the 13 employees had been trained in the operations conducted at two of the four workstations included in the evaluation. Thus, measurements were made at two workstations with these employees (see Table 1). The employees were all right-handed; 2 were male and 11 were female. They ranged in age from 21 to 47 years of age (mean ± standard deviation: 39.8 ± 8.0). Years experience working at this facility ranged from 2 months (~0.2 years) to 17 years (11.4 ± 6.0).

2.3. Apparatus and Instrumentation

A portable data acquisition system was used to collect the biomechanical data necessary to quantify manual forces associated with the screwdriver use. This system consisted of a portable "lunchbox" style pc (Broadax Systems Incorporated), Keithley Metrabyte DAS 1802HC A/D data acquisition card (12-bit), and signal conditioning hardware compatible with the force transducers described below. Software written in Labview (National Instruments, Austin, TX) controlled all of the data acquisition and digital signal processing. The digital sampling rate was 125 Hz for all force sensors and all signals were low-pass filtered with a 5-Hz cutoff frequency.

Two biomechanical measurements were made to quantify forces associated with the two driver processes. These measurements were of the grip/finger force on the handle of the screwdriver and the axial driver force transmitted vertically through the screwdriver in the screw insertion (see Figure 2). The grip/finger force between the user's hand and the screwdriver was measured with thin film pressure sensors (Tekscan, Flexiforce model

A101) attached over the finger segments of a "force glove." This system included hardware to provide excitation and amplification to 16 Flexiforce A101 sensors attached on a thin leather athletic grip glove worn by the subject to measure the distribution of finger force on the tools as these forces are distributed over the three phalangeal segments and metacarpal head of each finger. The model A101 sensors have a circular force sensing area of 1.4 cm diameter and a thickness of 0.127 mm.

The voltage outputs of the Flexiforce sensors were calibrated directly to force applied against a miniature button style load cell (Sensotec model 11, 50 lb. capacity). The Flexiforce sensors measure the normal force applied perpendicularly to their surface. The sensor was placed between a flat aluminum surface mounted over the load cell and the thumb tip of one of the investigators. By pressing with the thumb against the sensor over a metal surface and measuring this pressing force, the voltage output from the Flexiforce sensor could be regressed against the known force on the load cell and a linear regression relationship established. This scenario accurately reflects the loading of the sensors as it occurs when the sensors are attached to a glove worn by the subject while using the tool. The Flexiforce model A101 sensors exhibited linear relationships between output voltage and applied force as was described by Kong and Lowe (2005). Calibration of the sensors were made daily during the study period.

Axial driver force was measured on a force-sensing platform placed on the work surface underneath the workpiece and any fixturing/work-holding device at the workstation. The platform was constructed with four load cells (Transducer Techniques, model MLP) mounted in the corners between two 20-cm × 30-cm aluminum plates, each of 0.635 cm thickness. The platform was calibrated to applied load by summation of the responses of the four sensors. Prior to the recording of work cycles, static load readings were obtained to account for the mass of the work holding fixture and workpiece. This load was subtracted from the measured values to obtain the axial screwdriver force.

2.4. Procedure

Measurements of finger forces and axial driver force were obtained during the normal production activities at the workstations where testing took place. Assembly work at these workstations was performed by the employees in their normal standing position. The workstations generally had limited adjustability so that the orientation of the suspended screwdriver with respect to the employee was dependent on his/her stature. The screwdrivers were typically suspended above standing elbow height so that the employee's elbow flexion angle was often less than 90° at the point at which the screwdriver was initially gripped. The addition of the force-sensing platform under the work-holding fixture raised the work piece by 3 cm from its normal vertical orientation on the work surface. The tasks at each workstation involved a portion of the assembly of an external chassis of an automotive electronic component by the insertion of multiple small machine screws into a pretapped metal chassis. Each participant wore the force sensing glove on her/his right hand while the measurements were made. The force sensor glove did not interfere with participants' abilities to use the screwdrivers.

Each work cycle consisted of the insertion of between 4 and 11 screws, depending upon the work station (see Table 2). Work cycles were recorded individually, with trials recorded from multiple work cycles with the participant using both types of screwdriver. Four or five work cycles were typically recorded. These were not consecutive work cycles.

TABLE 2.   Workstations Included in the Evaluation, Number of Screws Inserted, and Time Between the Insertions of Each Screw

Workstation	Trigger start insertion time per screw (s) mean ± SD (n)	Push to start insertion time per screw (s) mean ± SD (n)	Potential reduction in cycle time using trigger driver (s)
AS2 (4 screws)	2.33 ± 0.42 (3)	2.64 ± 0.18 (3)	+1.24
OP2 (6 screws)	3.95 ± 1.10 (4)	3.88 ± 0.96 (4)	−0.42
Main Assembly 1 (9 screws)	2.28 ± 0.23 (6)*	2.95 ± 0.12 (6)*	+6.03*
Main Assembly 2 (11 screws)	2.23 ± 0.22 (6)*	2.91 ± 0.25 (6)*	+7.48*

Note. *n* reflects the number of employees in that condition. *Differences between trigger start driver and push to start driver are statistically significant ($p < .01$).

Video recording of the work cycles was made synchronously with the computer data acquisition of finger force and axial screwdriver force. The video recordings facilitated an analysis of upper limb posture (not reported in this article) and served as an archived record of the events occurring during the data collection. The computer data acquisition of the forces was initiated manually immediately prior to the first screw insertion and was terminated immediately after the insertion of the last screw.

2.5. Data Analysis

In postprocessing, an algorithm was developed to detect peaks in the axial driver force time series to identify the peak axial driver force associated with the insertion of each screw. It was assumed that the localized peaks in axial forces occurred at the instant each screw was firmly seated at the peak driver torque. This algorithm utilized the Labview "Threshold Peak Detector" function, which specifies a threshold amplitude and a width for valid peaks. A local maximum in axial force was identified for each screw insertion as shown in Figure 3. In most cases the local maximum axial force associated with each screw insertion was clearly identifiable, and the number of peaks detected by the algorithm correctly matched the number of inserted screws. In a few trials the number of peaks identified by the algorithm was inconsistent with the number of screws inserted. These cases were a result of the algorithm not being able to resolve a particular screw insertion clearly. These trials were examined manually for identification of the peaks associated with screw insertions.

   The peak axial screwdriver force associated with screw insertions was expressed as the average of the local maxima in axial driver force corresponding to the insertion of each screw in the work cycle. The measures of finger force included the total finger force associated with the peak axial driver force (total FF at peak AF) and the total finger force averaged over the entire trial recording (total FF averaged). The former was calculated as the average of all peaks associated with all screw insertions in the trial. The latter was calculated as the total finger force averaged over the entire trial time series. Total finger force was calculated by summing over all 16 force sensors. The percentage contribution of each phalangeal segment and each finger (sum of four individual segments)
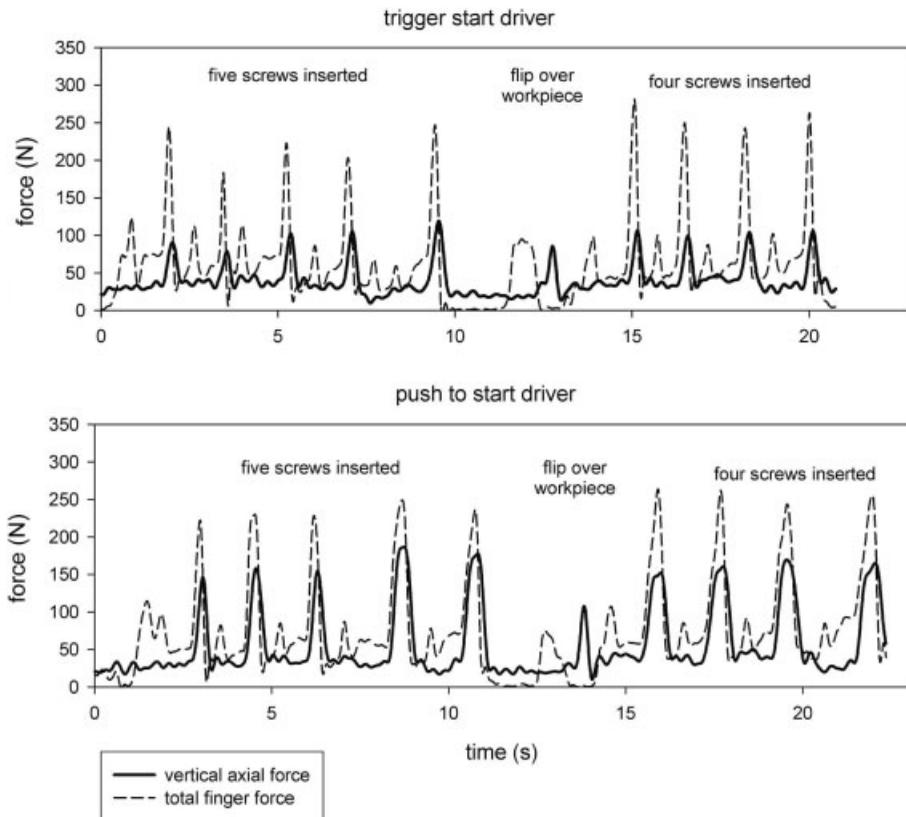
Figure 3   Example trial for the work process at Main Assembly 1. The nine screw insertions can be clearly identified by peaks in the vertical driver force time series. A clear peak in the vertical force measured on the force platform was identified in association with the rotation of the work-piece on the fixture. This peak was not included in the calculation of the peak vertical driver force.

to the total finger force was also calculated. Screw insertion time was calculated by the time period elapsing between the peaks in axial screwdriver force.

The data were analyzed with mixed models using the MIXED procedure from the computer program SAS® (Pre-Production Version 9.00, SAS Institute, Inc., Cary, NC). Employee subject was analyzed as a random effect. One employee was not included in the analysis with the mixed models because of missing data. Workstation (4 levels), screwdriver (2 levels), the Workstation × Screwdriver interaction, and experience were included as fixed effects. Contrasts were done to compare the screwdrivers at each workstation. Employee experience was scaled with three levels: less than 1 month, between 1 month and 1 year, and greater than 1 year working with the particular screwdrivers being evaluated in the study.

3. RESULTS

The push to start driver was associated with higher axial screwdriver forces and higher finger forces than the trigger start driver. The differences between the push to start and
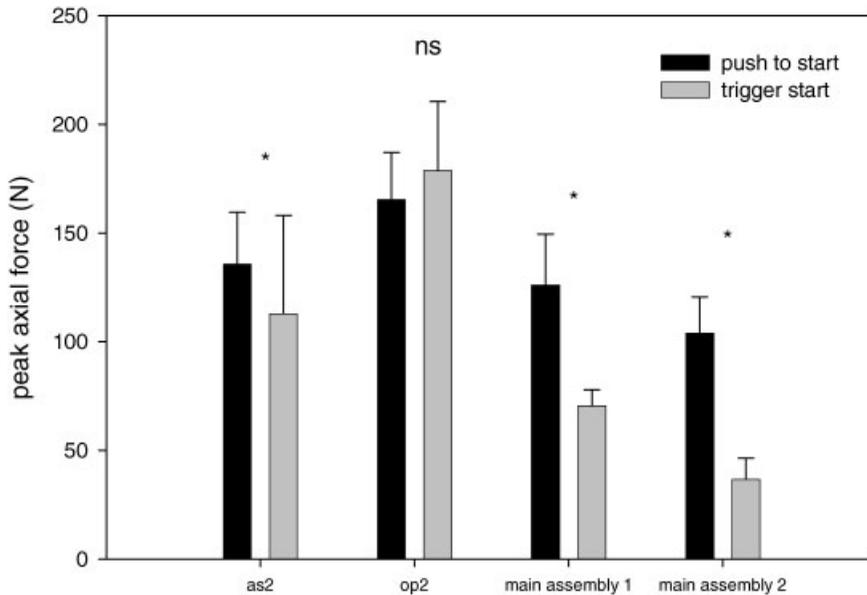
Figure 4   Peak vertical driver forces associated with each driver and workstation. Asterisk indicates that the difference between means are statistically significant at $p < .01$, ns indicates that the difference between the means is not significant.

the trigger start screwdriver axial forces were statistically significant ($p < .05$) at three of the four workstations (AS2, Main Assembly 1, and Main Assembly 2). The axial driver forces were not statistically different between the two screwdrivers at the OP2 workstation. (See Figure 4.)

With the knowledge that axial driver forces were generally higher for the push to start driver, finger forces were expected to follow the same trend. When the axial force is increased, grip force must be increased proportionately to prevent the screwdriver from slipping through the grip. Thus, the finger forces are a function of the axial driver force and the coefficient of friction between the hand and the tool grip surface. The measures of total finger force followed a pattern similar to that of the axial driver force. (See Figure 5.) The average total finger forces were significantly higher ($p < .05$) for the push to start screwdriver at workstations AS2 and Main Assembly 1 and the peak total finger forces were significantly higher for the push to start screwdriver at the Main Assembly 1 and Main Assembly 2 workstations. Total finger force was never significantly higher for the trigger start screwdriver.

To examine whether the higher finger forces associated with the push to start mode of activation were attributable to the higher axial driver force, the ratio of total finger force to the axial driver force was analyzed. Two ratios of these forces were calculated. The first was the ratio of the average total finger force for the trial to the peak axial driver force for screw insertions. The second was the ratio of the peak total finger force to the peak axial driver force for screw insertions. The ratio of total finger force on the grip of the screwdriver to the force transmitted with the screwdriver (axial force) is a general measure of how efficiently the finger force on the grip was transmitted into the functional force required of the tool. Table 3 lists the ratios of total finger force to peak axial force
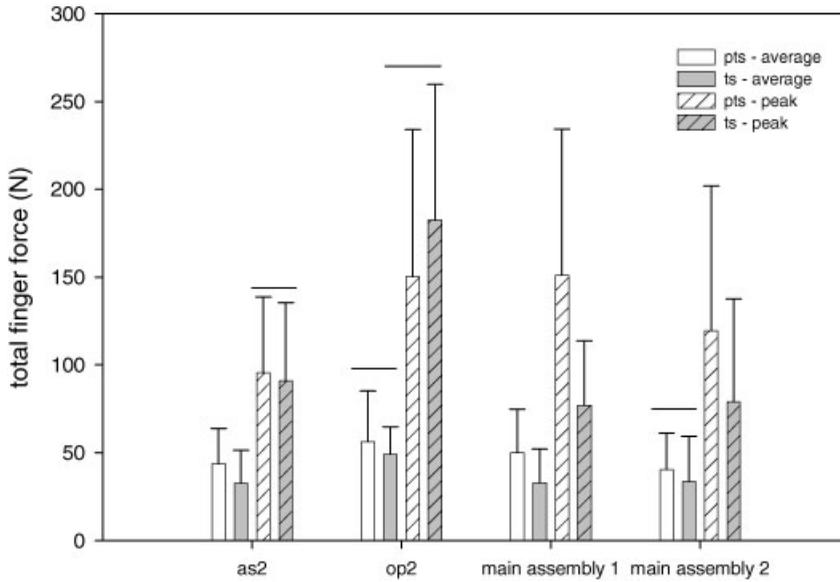
Figure 5   Total finger force (peak and average) associated with screw insertions shown by driver and work station. (PTS: push to start, TS: trigger start). Groupings under the horizontal bars indicate that the difference between means did *not* reach statistical significance with Type I error less than .05.

by workstation and screwdriver condition. Differences between the drivers were generally not statistically significant and the differences that were significant were cases in which the ratio for the trigger start driver was higher than that for the push to start driver, indicating less efficiency of the finger forces for the trigger start driver. In no case was the push to start driver associated with a significantly higher ratio of total finger force to peak axial driver force. Thus, in spite of exhibiting higher axial driver force and grip force, the push to start driver was associated with equal or greater finger force efficiency than the trigger start driver.

TABLE 3.   Ratios Between Total Finger Force (FF) and Peak Axial Driver Force (AF) for Trigger Start (TS) and Push to Start (PTS) Screwdrivers by Workstation

	Total FF averaged/peak AF			Total FF peak/peak AF		
Workstation	TS	PTS	Δ (TS − PTS)	TS	PTS	Δ (TS − PTS)
AS2	0.455	0.355	0.100	1.347	0.818	0.529*
OP2	0.248	0.313	−0.065	0.908	0.812	0.096
Main Assembly 1	0.419	0.377	0.042	0.996	1.110	−0.114
Main Assembly 2	0.699	0.395	0.304*	1.674	1.143	0.531*

*Difference is statistically significant at $p < .01$.

The grip force distribution on the screwdrivers was assessed by expressing each individual phalangeal segment force as a percentage of the total finger force and summing over all segments on each finger. The distribution of the total finger force across the four fingers was somewhat different for the two screwdrivers (see Figure 6). Finger force distribution was expressed as each individual finger's percentage contribution to the total finger force created by all four fingers in the grip of the driver. These finger force contributions were calculated from the total finger force at the instant of peak axial driver force. Index finger force contribution was significantly higher for the trigger start driver than for the push to start driver, $F(1,97) = 4.36$, $p < .05$. In contrast, the little finger force contribution was significantly higher for the push to start driver than for the trigger driver, $F(1,97) = 15.28$, $p < .001$. Middle finger and ring finger contribution to total finger force were not significantly different between the two drivers.

Analysis of the temporal spacing between axial driver force profile peaks indicated that screw insertions were slightly faster with the trigger start screwdriver (see Table 2). This difference was statistically significant at workstations Main Assembly 1 and Main Assembly 2. Based on the present study data, the assembly of a single unit was over 6 s faster with the trigger start screwdriver than with the push to start screwdriver at the Main Assembly 1 and Main Assembly 2 work stations. This reduction in assembly time was calculated as the reduction in individual screw insertion time multiplied by the number of screws inserted per work piece.
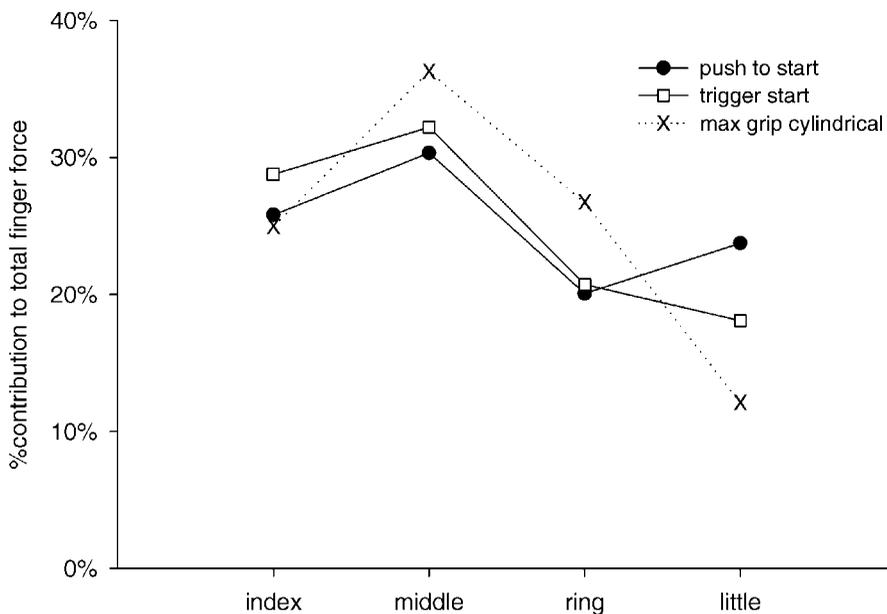

Figure 6   Distribution of finger force for the trigger driver and push to start driver. Differences between the index finger contribution and little finger contribution were statistically significant. The middle and ring finger contributions were not significantly different between the drivers. The finger force distribution associated with a maximum grip on a cylindrical handle is shown (from Kong and Lowe, 2005).

Intersubject variability among the measures of axial driver force appeared to be higher than that among the measures of total finger force. Comparisons of the ratios of between-subjects variance to the residual variance components for each measure yielded ratios of 2.99:1, 1.93:1, and 2.64:1 for the peak axial force, peak total finger force, and average total finger force, respectively. Conversely, finger force distribution, in terms of finger-specific percentage contribution to total finger force, exhibited much less between-subject variability. The ratios of between-subject:residual variance ranged from 0.99:1 to 1.52:1 for the percentage contribution of each of the four fingers.

Employee experience using each screwdriver had no statistically significant effects on any of the force measures.

4. DISCUSSION

Axial screwdriver forces with the push to start screwdriver were generally higher than those of the trigger start screwdriver. It is the higher axial driver force that appears to explain the higher finger forces observed with the push to start activation mode in the present study and that of Chang and Wang (2001). When expressed relative to the axial driver force, the push to start screwdriver finger forces are equal to, or slightly lower than, those of the trigger start driver. Thus, it appears that the higher total finger force associated with the push to start screwdriver are related to the higher axial forces associated with this driver. It is important to note that both the present study and that of Chang and Wang investigated the forces associated with one specific model push start and trigger start screwdriver.

Örtengren et al. (1991) reported axial forces, measured with a force transducer, associated with a pistol grip electric screwdriver and a manual screwdriver. The peak axial force applied with the screwdrivers in the present study, which averaged 110 N, was only slightly higher than the value of 104 N (averaged across all treatment conditions) reported by Örtengren et al. Because it is not clear from their paper whether the reported force values represent average axial driver force over the duration of the screw insertion or the peak axial driver force associated with screw insertions, a direct comparison of these values with those measured in the present study is not possible. Nonetheless, the forces measured in the two studies are similar. In the present study local peaks in the axial screwdriver force time series could be clearly identified and matched with the individual screw insertions observed. However, measuring the average axial driver force associated with each screw insertion was less straightforward because identification of the precise beginning and end of each screw insertion was not always completely clear.

A difference between the studies of Örtengren et al. (1991) and Freund et al. (2000) and that of the present study that may affect the comparison of the axial driver force data is the fact that the present study examined these forces in actual assembly operations in a manufacturing facility and the other studies examined these forces in laboratory-based tasks. It is likely that the time stresses associated with work-cell-paced assembly typical in a manufacturing environment will result in different force profiles than a laboratory simulation in which production rate and time stress demands cannot be realistically simulated.

Chang and Wang (2001) measured individual contact forces between the fingertip and screwdriver handle at the distal phalanges and reported the sum of these distal phalangeal forces as a measure of total finger force. The total finger forces they reported averaged

approximately 29 and 31 N for the trigger and push to start drivers, respectively. In the present study the total distal phalangeal forces were 40 and 57 N at peak force (for trigger and push to start drivers, respectively) and 14 and 20 N when averaged over the trial. Because the average total finger force values measured in the present study included brief periods of time when the worker's hand was not in contact with the tool (zero finger force), the range of the distal phalangeal forces observed in the present study are consistent with those reported by Chang and Wang. However, in the present study, all of the phalangeal segments' contributions to total finger force were included (distal, middle, proximal, and metacarpal heads). The proximal and middle phalanges and metacarpal segments accounted for 59% of total finger force in the present study whereas the distal phalanges accounted for 41%.

The distribution of the distal phalangeal forces of Chang and Wang (2001) were also similar to that found in the present study and, like the present study, suggest a larger relative contribution of the little finger (see Figure 7) to total finger force than would be expected. One of the advantages of the force glove system used in the present study was the ability to measure individual forces generated by all phalangeal segments and sum these phalangeal forces in a more complete measure of individual finger force. Figure 6 illustrates that when all phalangeal segments are included in the total finger force measure, the percentage contribution of the four individual fingers to the total finger force is closer to that observed in maximum grip exertions on cylindrical handles (Kong & Lowe, 2005) in which the relative contribution of individual fingers is more proportional to the physiological cross-sectional area of the extrinsic finger flexors (An, Chao, Cooney, & Linscheid, 1985; Freund & Takala, 2001).
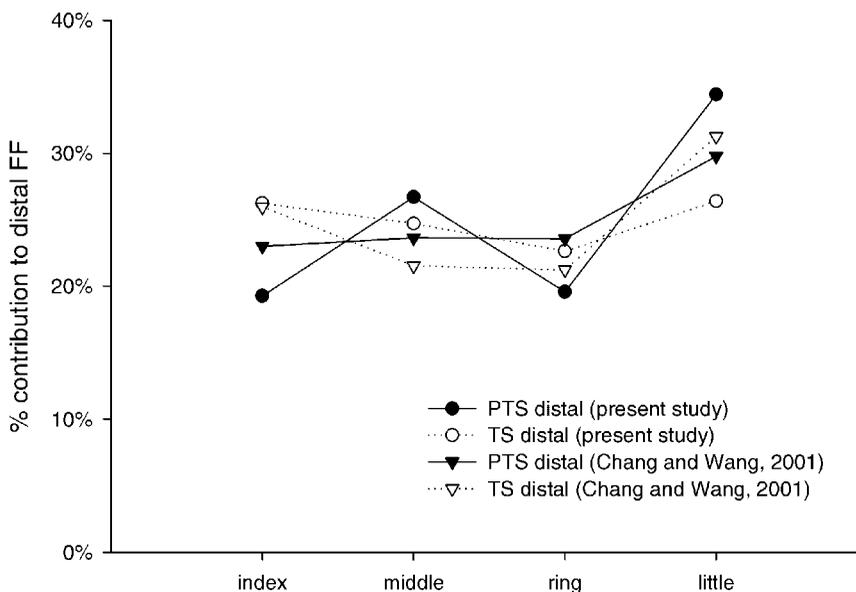

Figure 7   Contributions of the distal phalange force of each finger to the total distal phalangeal force shown as a function of screwdriver for the present study and that of Chang and Wang (2001). Both studies show a high percentage contribution from the distal phalange of the little finger.

Although the glove-based measurement approach adopted in the present study overcomes several limitations associated with the direct attachment of force sensors to the tool, it is not without limitations. The glove-attached force sensors measure phalangeal segment forces that, when summed, are not equivalent to the total hand force because the handle and hand make contact in other palmar regions where there are no sensors. Further, the synthetic leather material of the glove does alter the frictional conditions between the hand and handle material and may degrade tactile feedback at the grip interface, which may thus alter the grip force on the tool handle (Kinoshita, 1999). However, in our view, the ability to evaluate the finger/grip force distribution on any tool handle, of any shape, size, or material, with repeatable placement of the force sensors relative to the subject's hand justifies the acceptance of the limitations imposed by the glove-based measurement system. Chang and Wang (2001) attached thin film force sensors directly to the pulpar regions of the distal phalanges of subjects. This direct attachment of the force sensors to the fingertip surface also alters the frictional conditions between the hand and the tool handle because the sensor material, rather than the pulpar skin, is in contact with the tool handle. The thin synthetic leather gloves used in the present study were between 0.3 and 0.5 mm in thickness and the Flexiforce sensors attached over the phalangeal segments of the glove added only 0.13 mm thickness over these regions. Further, several of the employees who participated in the study wore gloves while performing the assembly work and thus merely exchanged their normal work glove with our "force glove" to participate in the study.

At two of the workstations in this study some of the screwdrivers were equipped with a thin layer of anti-static (ESD) conductive shielding tape attached over the grip area. Thin layers of materials wrapped around the handle of the driver, such as ESD tape, may also affect the coefficient of friction between the hand and the driver grip surface or counteract the benefits of a textured grip surface. A reduction in the friction and/or the effectiveness of the handle texturing will likely increase the grip force required to create equivalent vertical driver force. It is difficult to measure the coefficient of friction between human skin and materials such as ESD tape; thus we were not able to determine whether a reduction in friction existed or whether it would be significant in increasing hand force in a bare-handed situation. Studies have demonstrated that smooth polished surfaces reduce the friction between the palmar skin and tool grip surfaces, requiring higher grip force to exert the same level of force with the tool (e.g., Buchholz, Frederick, & Armstrong, 1988).

The design concept behind the push to start screwdrivers is that, by requiring axial force to activate the driver, a more secure contact is maintained between the screwdriver bit and the fastener head. The more secure contact reduces bit wear and damage to the fastener head referred to as "cam-out," which results from inadequate axial force applied against the fastener head. Thus, the push to start activation mode may have benefit on product quality in some instances at the expense of increasing the forces exerted by the operator. In situations where cam-out does not significantly threaten product quality the advantages of the push to start drivers are unclear. In the present study all of the assembly operations investigated involved the insertion of Phillips head screws. The findings of Örtengren et al. (1991) indicate that inserting and seating TORX head screws requires less axial force at a given level of torque. Thus, an alternative to changing the screwdriver design to reduce problems with cam-out and physical stress on the operator may be to adopt TORX head screws in place of the Phillips head.

The finding that the trigger start screwdriver was associated with less axial screwdriver force and less total finger force on the handle may have been partly attributable to the employees having more experience using this driver. One of the criteria for eligibility to

participate in the study was experience using both the trigger and push to start screwdrivers; however, it appeared that employees tended to have more experience using the trigger start screwdriver than the push to start screwdriver. No statistically significant effects were found for employee experience on any of the biomechanical forces measured when experience was scaled under an ordinal, three-level scaling framework. A more refined method of scaling employee's experience with the drivers was not feasible as several employees could not reliably recall the length of time they had used the particular screwdrivers. Anecdotally, the majority of participants reported that they preferred the trigger start screwdriver, but it is not clear whether this preference was influenced by their greater level of experience using the trigger start screwdriver.

The push to start screwdriver investigated in the present study had a small flange at the base of the grip area. (See Figure 1b.) In theory, a protruding flange could allow arm force to be transferred through the edge of the palm (side of the fifth metacarpal and phalanges) into axial driver force with less grip contact force on the palm of the hand. The amount of the total arm force transferred into axial driver force through the flange relative to that transferred through shear forces created at the contact between the handle and the palm is not known. However, because the total finger force associated with the push to start driver was higher than that for the trigger start driver, it can be inferred that the flange was not particularly effective in providing mechanical advantage in the transfer of arm force.

When employees are trained in assembly with electric or pneumatic screwdrivers, they may benefit from training to determine the minimum amount of axial driver force exertion necessary to seat the fastener firmly. It is common for individuals to apply more force than is required to complete manual tasks, particularly as related to grip force, where an overgripping control strategy is adopted to insure a margin of safety (Cole, 1991; Kinoshita, 1999; McGorry, 2001; Westling & Johansson, 1984). Data regarding the minimum required axial screwdriver force and the minimum required grip force were unavailable for the tasks examined in this study. However, the intersubject variability in measured axial screwdriver force suggests variability in the efficiency with which employees performed the tasks. (Efficient performance is defined in this case as exerting the minimum screwdriver forces necessary to insert the fastener.) Awareness of the benefits of good ergonomic work practices may reduce the amount of excessive force employees exert when using in-line electric screwdrivers.

5. CONCLUSION

The findings of this study indicate that the electrically powered in-line screwdriver with a push to start mode of activation was associated with higher axial driver force than the trigger start screwdriver used in the same screw insertion tasks. The increased finger forces observed in association with the push to start mode of activation found in this and other previous studies are likely to be related to this higher axial force. By requiring an application of axial force to engage the starting mechanism, the push to start screwdriver design may afford the exertion of greater axial force, and thus grip force, than the trigger start screwdriver design. The purpose of the axial screwdriver force is to insure adequate contact between the screwdriver bit (Phillips in this study) and the head of the screw while the screwdriver torque rotates the screw. Employees working with electrically or pneumatically powered screwdrivers could be instructed to exert the minimum amount of axial screwdriver force necessary to firmly seat the fastener while avoiding the problem of cam-out in the fastener head.

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