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Finger Tendon Travel Associated with Sequential Trigger Nail Gun Use

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TECHNICAL ABSTRACT

Background—Pneumatic nail guns used in wood framing are equipped with one of two triggering mechanisms. Sequential actuation triggers have been shown to be a safer alternative to contact actuation triggers because they reduce traumatic injury risk. However, the sequential actuation trigger must be depressed for each individual nail fired as opposed to the contact actuation trigger, which allows the trigger to be held depressed as nails are fired repeatedly by bumping the safety tip against the workpiece. As such, concerns have been raised about risks for cumulative trauma injury, and reduced productivity, due to repetitive finger motion with the sequential actuation trigger.

Purpose—This study developed a method to predict cumulative finger flexor tendon travel associated with the sequential actuation trigger nail gun from finger joint kinematics measured in the trigger actuation and productivity standards for wood-frame construction tasks.

Methods—Finger motions were measured from six users wearing an instrumented electrogoniometer glove in a simulation of two common framing tasks–wall building and flat nailing of material. Flexor tendon travel was calculated from the ensemble average kinematics for an individual nail fired.

Results—Finger flexor tendon travel was attributable mostly to proximal interphalangeal and distal interphalangeal joint motion. Tendon travel per nail fired appeared to be slightly greater for a wall-building task than a flat nailing task. The present study data, in combination with construction industry productivity standards, suggest that a high-production workday would be

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OCCUPATIONAL APPLICATIONS

This article reports a method for assessing finger tendon motion associated with the use of a sequential actuation trigger pneumatic nail gun. The two-stage actuation process of the sequential actuation trigger reduces risk of nail puncture injury from unintended nail discharge (relative to the higher risk of the contact actuation trigger). However, widespread adoption of the sequential actuation trigger nail gun throughout the construction industry has been hindered by beliefs about productivity and musculoskeletal concerns about the repetitive trigger actuation and finger motion for each nail fired. Though existing guidelines for finger tendon travel exposure are not well established, predictions derived with the present method combined with productivity standards suggest insufficient evidence to contradict the safety-based recommendation to adopt the sequential actuation trigger trigger.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

associated with less than 60 m/day cumulative tendon travel per worker (based on 1700 trigger presses/day).

Conclusion and Applications—These results suggest that exposure to finger tendon travel from sequential actuation trigger nail gun use may be below levels that have been previously associated with high musculoskeletal disorder risk.

Keywords

Nail gun; trigger; repetitive motion; finger tendon

INTRODUCTION

The objective of this study was to derive a method to predict cumulative tendon travel exposure for the index ringer during the use of a sequential actuation trigger (SAT) pneumatic nail gun. All pneumatic nail guns include a safety feature requiring that the spring-loaded safety tip make contact with the workpiece before a nail can be fired. However, two fundamental trigger (i.e., actuation) systems are available with these tools. A contact actuation trigger (CAT) allows the operator to fire successive nails by holding the trigger depressed and repeatedly pressing the nose of the gun against the work surface. (This is colloquially referred to as “bump firing” the nail gun.) The SAT system involves a two-stage process and requires that, for each nail discharged, the trigger be depressed after nose contact is made with the workpiece.

During the period 2001–2005, 22,000 occupational and 15,000 non-occupational nail gun injuries/year were treated in emergency rooms (MMWR, 2007). These injuries were particularly problematic in the residential construction industry. Lipscomb et al. (2003) investigated 783 injuries among a cohort of union carpenters (*n* = 5137) working in the residential building industry during 1999–2001 and showed that 14% of the injuries involved nail gun use. The overall nail gun injury rate based on hours worked in the residential sector for this time period was 2.1/200,000 hours. Rates varied with experience, with the rate for apprentice carpenters being higher (3.7/200,000 hrs). Lipscomb et al. (2003) concluded that approximately two-thirds of nail gun injuries could have been prevented if the nail gun had been equipped with an SAT. In spite of the clear evidence showing safety benefits of the SAT, this trigger system has not been universally adopted. Two perceptions appear to be common barriers to adoption. First, CATs are perceived as being associated with greater productivity because they afford a faster rate of nail fire under certain conditions. Second, a perception exists that repetitive triggering of the SAT may result in musculoskeletal symptoms because of the need to repeatedly actuate the trigger with flexion of the index finger.

The present study represents a portion of a larger project to explore construction industry perceptions about the SAT system and the repetitive motion risk factors it is perceived to create. This article reports a method developed to quantify cumulative tendon travel exposure associated with repetitive index finger motion with an SAT nail gun.

METHODS

Study Design

Two tasks common in wood frame construction processes were simulated. These were *flat nailing* and *wall building*. Flat nailing refers to a subflooring or sheathing application task in which the nail gun is oriented vertically and many nails are discharged in succession to fasten sheet material to a joist or framed understructure. Flat nailing is typically associated with a linear progression of nail fastening along the length of joists with movement of the tool to equidistant points of nail application. This rhythmic motion of the nail gun lends itself to a faster movement of the tool and higher rates of nail application, relative to a task in which the nail fastening is not performed along a linear path in a rhythmic manner. Wall building refers to the task of framing walls with dimensioned lumber. The wall-building task simulated in this study was the fastening of a vertical “2 × 4 stud” (3.81 cm × 8.89 cm) to a 2 × 4 horizontal plate, forming the bottom and top of the wall. In this task, the opposite hand positions and holds the stud in place, at least initially, as the nail is discharged through the plate into the bottom of the stud. A modification was made to this general process for the purpose of participant safety (see the “Procedures” section).

Two common pneumatic framing nail gun models were included in the study, each firing 82.55-mm (3.25-inch) framing nails. These nail guns were not chosen for specific aspects of their trigger design but rather because they were believed to be two of the more commonly used models in the industry. Nail gun A had mass of 3.85 kg and a 21° magazine angle; nail gun B had mass of 3.89 kg and a 30° magazine angle. Magazine angles are the angles at which the nails feed into the firing chamber from the sleeve in which the nails are held. The two nail guns had different trigger designs (see Fig. 1). Nail gun A had a selectable trigger mechanism that allowed the user to select sequential or contact actuation firing modes. Nail gun B had a longer, flatter trigger surface, and the plastic trigger insert piece had to be switched to change between the SAT and CAT modes. (Only the SAT version of each nail gun was tested in this study.) The wall building trials were conducted before the flat nailing trials because the actual construction of walls and partitions occurs without any sheathing material already attached to the studs.

Participants

A convenience sample of six male participants completed the study. These participants were not occupational users of pneumatic nail guns, although some had experience using nail guns in various home improvement projects. Since hand anthropometrics influence finger joint displacement with trigger use, participants with a range of hand sizes were recruited in the convenience sample. These individuals were unpaid volunteers. The study protocol was reviewed and approved by the organization’s institutional review board. Participant height and body mass were self-reported, while hand anthropometric measures were obtained using digital calipers (Table 1).

Apparatus

Finger joint angles were measured with the CyberGlove (Immersion Technologies, San Jose, CA, USA). The CyberGlove was worn on the subjects’ dominant (right) hand. The

CyberGlove is a Lycra glove, form fitting to the hand, with embedded joint motion sensors spanning the joints of the hand. Acquisition of the serial byte stream from the CyberGlove interface unit was obtained by a custom LabView (National Instruments, Austin, TX, USA) virtual instrument interface. Sampling rates were in the range of 40–50 Hz and were limited by the CyberGlove serial interface unit.

Prior to collecting finger kinematics in the nailing tasks, the CyberGlove device was calibrated on each participant's hand. The calibration procedures were as follows.

1. The participant assumed three bare-handed static reference poses placing the distal interphalangeal (DIP), proximal interphalangeal (PIP), and metacarpal phalangeal (MCP) joints in reference angular positions, and these joint angles were measured manually for each finger with a baseline (model #12-1015, 89 mm) stainless steel finger goniometer (see Fig. 2). The reference poses were a cylindrical grip of an 87-mm-diameter pipe, a cylindrical grip of a 38-mm-diameter pipe, and an open flat-hand position (assumed to be 180^c included joint angles). Finger joint angles associated with these poses were intended to span the range associated with angular finger positions during trigger press.
2. The CyberGlove was donned and the static hand reference poses were repeated while joint position data were recorded from the CyberGlove for 5–10 s.
3. Linear regression analysis was used with the manually measured joint angle serving as the single predictor variable. A total of 12 linear regression equations were fit—one for each finger (4) × joint (3). Three calibration points established each individual regression. Coefficients of determination (r^2) exceeded 0.95 in almost all cases and had means of 0.989, 0.987, and 0.987 for the MCP, PIP, and DIP joints, respectively.

Procedures

Wall-Building Task—The wall-building task had five points of fastening along the 2.44 m (8 foot) length of the bottom plate. To conserve lumber, the five vertical wall studs were spaced 0.406 m (16 inches) apart and were only 0.33 m (13 inches) long rather than the typical 2.44 m (96 inches) "king stud." Thus, the lumber held in place was much shorter than an actual king stud. Safety concerns about holding a short piece of lumber in place with the opposite hand during nailing warranted the construction of a shielding device to serve as a sham stud (see Fig. 3). The sham stud was a 0.305 m (12 inch) length 2 × 4 with side brackets slotted to accept a 0.25 m × 0.25 m piece of translucent Lexan™polycarbonate (13 mm thick) to protect the participants' opposite hand/arm from a puncture injury. The shield was angled 30° downward from the vertical and 30° away from the plane of the long plate 2 × 4, so that any nail ricochet off the shield would be directed down and away from the participant (see Fig. 3.) The weight of the shield/sham stud assembly was 1.76 kg, approximately 37% of the weight of a 2.44 m (8 ft) 2 × 4 (approximately 4.75 kg).

Two nails were fastened at each marked location on the 2 × 4 plate as if a stud were actually being fastened to a bottom plate. The nails protruded through the plate into the gap in the sham stud fixture. The sham stud/shield fixture could then be transferred into place at the next point of fastening 40.6 cm (16 inches) away. There were ten nails fired per trial–two nails applied at each of the five points at 40.6 cm centers on the bottom plate. One trial was conducted per treatment condition.

Flat Nailing Task—The flat nailing trials required the participant to fasten 16 mm (0.625 inch) oriented strand board sheathing to the framed perimeter. Nails were applied along the long edge of the 2.44 m (8 ft) frame at approximately 15.2 cm (6 inch) spacing intervals. Thus, approximately 17 nails were fastened in a given trial, in which 1 edge of the 2.44-m-long sheathing was fastened. Results for two trials were averaged–one trial for each long edge of the sheathing.

Tendon Travel Model and Data Analysis

Joint kinematics of the index finger in the nailing tasks were characterized by an ensemble average joint angle time series calculated for each trial (see Fig. 4). The peak index finger flexion angle was used as an event mark to define a single nail firing cycle, assuming that the trigger actuated when the finger was maximally flexed. This was the instant when the sum of the finger joint displacements was at its maximum. The ensemble average was derived by first calculating the mean cycle duration. Individual nail cycles were then resampled to normalize the individual cycle to the mean cycle duration. Subsequently, all temporally aligned cycles were averaged at each time interval to create the ensemble average (see Fig. 4). Flat nailing trials were analyzed based on a single nail per cycle. Because the wall-building task involved the application of two nails per stud, the ensemble average was calculated for a cycle consisting of two nails.

Predictions of flexor tendon travel were based on equations derived by Armstrong and Chaffin (1978) in cadaveric studies. These regression equations predict tendon displacement for flexor digitorum profundus (FDP) and flexor digitorum superficial (FDS) as a function of DIP, PIP, and MCP joint angles. The equations for FDP and FDS tendon displacement (in mm) are as follows:

$$FDP=\theta_m(0.0872+0.004211T_m)+\theta_p(0.09356+0.004211T_p)+\theta_d(0.01902+0.004211T_d), \quad (1)$$

$$FDS=\theta_m(0.1034+0.004211T_m)+\theta_p(0.07297+0.004211T_p)+\theta_d(0.03522+0.004211T_d), \quad (2)$$

where

θ_i is the joint angle (in degrees), measured as complement of the included angle between segments; m = MCP joint, p = PIP joint, d = DIP joint; and

T_i is the joint thickness (mm).

Tendon travel was calculated using Equations (1) and (2) from incremental differences in tendon displacement between successive points in the ensemble average time series. The absolute values of incremental tendon travel were summed to yield total tendon travel for a cycle. Total tendon travel was halved for the wall-building trials, because the ensemble average cycle was characterized for two nails. This yielded total tendon travel per nail.

The percentage contribution of each finger joint to total tendon travel was also calculated. Individual joint (PIP, DIP, and MCP) tendon travel was calculated from the relevant joint component in Equations (1) (FDP tendon) and (2) (FDS tendon). Total tendon travel for each joint was determined by summing the absolute values of incremental tendon travel for the specific joint. The percentage contribution for the joint was the total for the individual joint divided by the total tendon travel. Six dependent variables for tendon travel (two tendons with three joint-level displacement contributions) were obtained: FDP_MCP, FDP_PIP, FDP_DIP, FDS_MCP, FDS_PIP, and FDS_DIP. FDP_TOTAL and FDS_TOTAL were calculated from the sum of individual joint-level tendon displacements.

Erroneous readings for DIP joint displacements were observed for one participant and were removed from the analyses. Missing data were replaced by the Markov chain Monte Carlo method with a single chain to create five imputations (Schafer, 1997). The joint distributions of FDP_MCP, FDP_DIP, and FDP_PIP were used to impute values of FDP_PIP, while the joint distributions of FDS_MCP, FDS_DIP, and FDS_PIP were used to impute values of FDS_PIP. Separate imputations were done for each combination of nail gun and task. The sums of the sets of variables (FDP_TOTAL and FDS_TOTAL) were calculated after the imputation. For variables with missing data (FDP_DIP, FDP_TOTAL, FDS_DIP, and FDS_TOTAL), means and standard errors of the variables were calculated for each imputation, and the results were combined to calculate 95% confidence intervals of the mean. For variables with non-missing data, confidence intervals were calculated assuming normality using the *t* distribution. All calculations were done with SAS® (Version 9.2, SAS Institute Inc., Cary, NC, USA).

RESULTS

Most finger tendon travel in the actuation of both nail gun triggers was attributable to interphalangeal joint motion (PIP and DIP). From the most flexed position (trigger depressed) to the most fully extended position (trigger released), mean MCP joint angular displacements were 3.9° and 8.7° for nail guns A and B, respectively; PIP joint displacements were 25.4° and 39.6° for nail guns A and B, respectively; and PIP were 38.5° and 36.8° for nail guns A and B, respectively.

MCP flexion accounted for 16% of the total tendon travel for nail gun A and 22% for nail gun B. PIP and DIP flexion accounted for 42% and 41% of tendon travel for gun A and 47% and 31% for gun B, respectively. A summary of predicted tendon travels per nail fired are shown in Fig. 5.

Qualitatively, flat nailing appeared to involve less tendon travel per nail fired than did wall building, and there were also differences between the nail guns, with nail gun A having less tendon travel.

Figure 6 shows the cumulative tendon travel as a function of the number of nails fired for the four trigger × task conditions. These plots show predicted cumulative tendon travel (in meters) as a function of the number of nails fired. Alternatively, given a level of cumulative tendon travel determined to be an acceptable limit, the corresponding number of nails associated with that limit could be predicted.

DISCUSSION

The reported method was used to predict tendon travel per individual trigger press to discharge a single nail with an SAT nail gun. Calculating finger flexor tendon travel on a per nail fired unit of analysis is advantageous, because cumulative tendon travel exposure can then be more readily estimated based on daily production output. If tendon travel had been calculated from finger kinematics measured over a sampling period without knowledge of the number of nails fired, estimated cumulative exposure could not be related to production output.

The observed finger displacements with the SAT suggest a deliberate release of the trigger and movement of the finger away from the trigger after each nail discharge. The actual range of linear displacement of the triggers is only a few millimeters and appears to require significantly less finger joint motion than was observed. The increased finger joint displacement (and resulting tendon travel) in the wall-building task may be attributable to an even greater degree of deliberate movement of the finger away from the released trigger, where more critical movement and positioning of the nail gun and accurate placement of the nails is required. Differences between the nail guns would likely be due to differences in trigger reach distances, with nail gun B requiring greater flexion of the index fingers and, thus, a greater range in displacement of the joints to close the trigger.

It is illustrative to consider flatwork (e.g., sheathing or subflooring), as it represents a higher nailing production output example in the residential construction sub-sector, wherein pneumatic nail gun use is ubiquitous and nail gun injuries are most prevalent (Baggs et al., 2001). One source for this productivity information is the Means Productivity Standards for Construction (R.S. Means, 1994) and the R.S. Means (Norwell, MA) CostWorks® 2012 cost estimator, which are resources used for estimating and costing standardized construction tasks. The standards specify a conversion factor of 0.009–0.010 labor hours per square foot of pneumatically nailed plywood CDX subflooring. This is equivalent to a carpenter fastening 25–28 sheets of 1.22 × 2.44 m (4 × 8 ft) material. If each sheet is assumed to be fastened with 60 nails, this would translate to a daily production of 1680 nails *per carpenter*. If the nailing were distributed between two carpenters (as indicated by the standard) using SAT nail guns, the total tendon travel exposure would be 22–41 m/day or 37–60 m/day (per carpenter) for nail guns A and B, respectively (from Fig. 6). The published productivity standards should be considered cautiously, however, as the authors are aware of one specialty framing contractor using an estimate equivalent to 0.0042–0.0050 labor hours/ square foot for sheathing and flat nailing in new residential construction. This would equate to approximately 3500 nails per day per carpenter, suggesting that the productivity standards substantially under-predict nailing output in this task. (Vertical dashed lines in Fig. 6 represent the output levels of 1680 and 3500 nails in the flat nailing task scenario.) Regardless of which productivity rate is applied to predict actual output, the above example, which assumes 8 hours of consecutive flat nailing, is believed to represent an atypically high day’s exposure to nailing for a single carpenter. The Fig. 6 graphs for predicted tendon travel in wall building are shown without productivity estimates because wall building is associated with far fewer nails fired per unit of working time and, accordingly, represents a much lower risk task than flat nailing.

To the authors' knowledge, there are no guidelines for safe exposure to cumulative daily tendon travel applicable to index finger triggers. However, a study by Sommerich et al. (1996) assessing cumulative tendon travel with keyboard use provided a basis for comparison. Sommerich et al. (1996) measured joint motion and assessed cumulative tendon travel for a full workday among a group of four data entry operators. Cumulative tendon travel predictions were 86, 124, 149, and 273 m/day. Previous data by these authors on musculoskeletal disorder risk classification were used to propose daily tendon travel exposure limits of 55 m (low risk) and 145 m (high risk). Comparison of this study's data with these proposed limits suggests that the cumulative tendon travel associated with the SAT nail gun would not be characterized as high risk. The 55 m/day and 145 m/day low and high risk limits have not been validated for repetitive trigger actuation with the index finger, but the authors are unaware of any similar data related to trigger-actuated tool use. Another potential limitation is that tendon travel predictions in both studies were based on tendon travel displacement from joint motions of cadaveric specimens.

Index finger flexor tendon travel with use of a nail gun trigger is influenced largely by PIP and DIP joint motion as opposed to keyboard work, which may be more influenced by MCP joint motion. Another consideration is that the present tendon travel predictions did not include wrist motion. However, in the flat nailing task, with the workpiece laying horizontally at floor level, wrist motion was not likely a significant issue as the nail gun was oriented vertically with a neutral wrist posture. Flat nailing tasks are those in which there is greater potential for faster nailing, and use of the SAT has been questioned with regard to the potential for repetitive motion injury. Another consideration with applying exposure limits for keyboard use (Sommerich et al., 1996) to nail gun trigger use is that differences in tendon forces between the activities are not considered.

The well-intentioned recommendation to deliberately remove the finger from the trigger when holding the nail gun but not nailing is an obvious precautionary practice for traumatic injury prevention. However, with existing nail gun designs, this practice removes the index finger from contributing to gripping of the tool, and the index finger would otherwise contribute approximately 28% to the total cylindrical power grip (Freund & Takala, 2001; Kong & Lowe, 2005). Workers may be faulted for holding the nail gun with the trigger depressed when not actively nailing; however, this practice makes more efficient use of the hand in its capability to grip the tool.

The contribution of the present study is the method and resulting prediction of finger tendon travel for the purpose of understanding repetitive motion associated with use of the SAT nail gun. The present findings do not address all potential musculoskeletal risk factors associated with nail gun use, and other criteria, in addition to repetitive finger motion, finger tendon travel, and potential tenosynovitis (trigger finger), should also be considered. A valid criticism of the present analysis of tendon-related risk attributable to the SAT is that it is incomplete without consideration of the tendon *forces* in the repetitive actuation of the trigger. However, the finger forces in the grip required to statically support the 3.6 kg mass of the nail gun, *independent of the trigger system*, may account for the majority of the cumulative tendon force. Additional work is being conducted to evaluate upper limb loads created by the duration of supporting the nail gun mass, the cumulative force exerted in repetitively pressing the safety tip against the work piece, and how these are affected by the trigger system.

The present results for predicted finger tendon travel, when scaled to represent higher production nail gun use in residential construction, suggest cumulative levels of tendon travel that would not be considered high risk in comparison to suggested exposure limits. While acknowledging caution in applying these limits, it is suggested that cumulative tendon travel generally poses low risk to moderate risk for very high-volume work. Current evidence appears insufficient to contradict the safety-based recommendation to adopt the SAT trigger for traumatic injury prevention.

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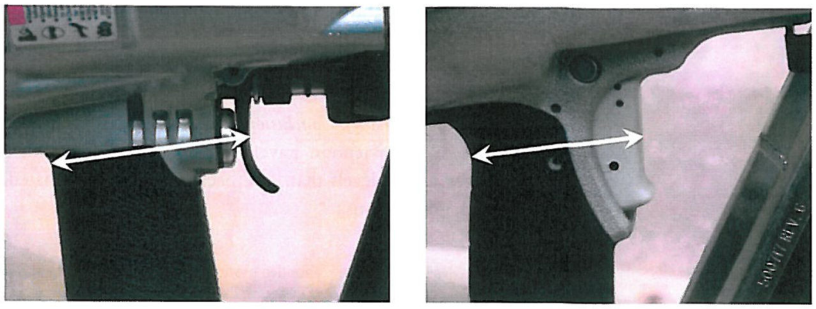

FIGURE 1.

Triggers for nail gun A (left) and nail gun B (right). The trigger reach distance (shown with arrows) for trigger A was 66 mm and for trigger B was 55 mm (color figure available online).

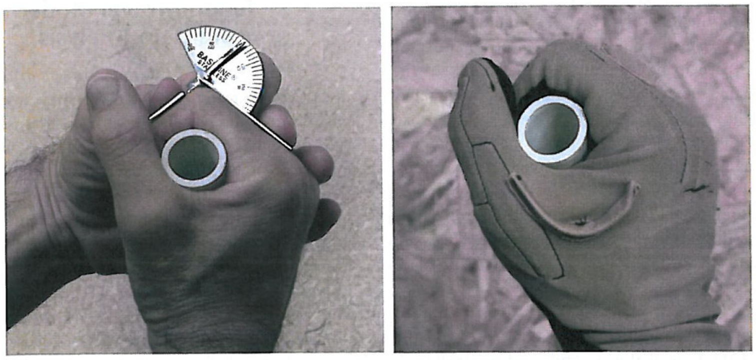

FIGURE 2.

Manual goniometric measurement of the PIP joint angle (left), for calibration of the CyberGlove (right) (color figure available online).

FIGURE 3.
Wall-building task with user holding the sham stud/shielding fixture with the opposite hand (left). The nails protruded through the gap between the slotted side brackets of the device into which the shield was inserted. The sham stud held in the hand was not actually fastened to the plate 2×4. The shield served to protect the opposite hand from injury in the flat nailing task, in which the opposite hand is uninvolved (right) (color figure available online).

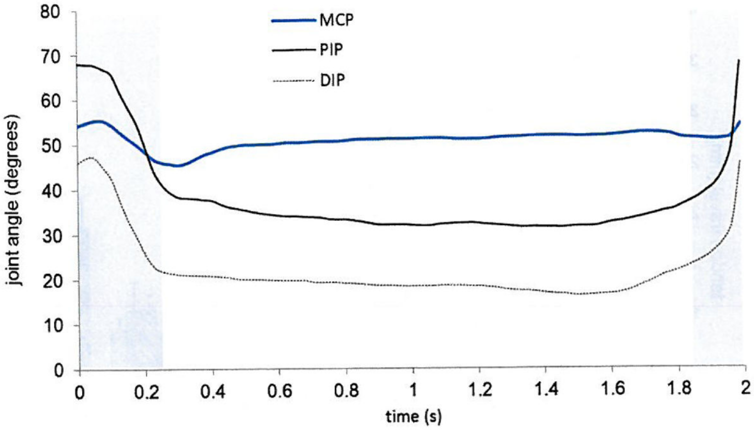

FIGURE 4.

Example of calculated ensemble average for index finger joint angles in a flat nailing trial (single nail). Joint angles are expressed as the angular difference from a straight index finger (180° minus the included joint angle between phalangeal segments). Shaded areas approximate the period in which the trigger is depressed, with peak finger flexion occurring at time 0 (color figure available online).

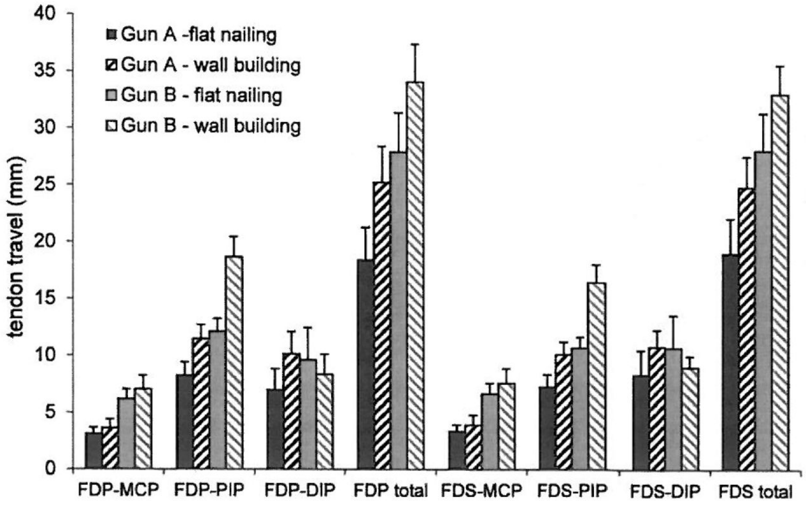

FIGURE 5.

Predicted tendon travel per nail fired. The first abbreviation refers to the finger tendon (FDP or FDS), and the second abbreviation refers to the amount of tendon travel about the joint (MCP, PIP, or DIP). Total refers to the summed tendon travel. Mean plus standard error is shown.

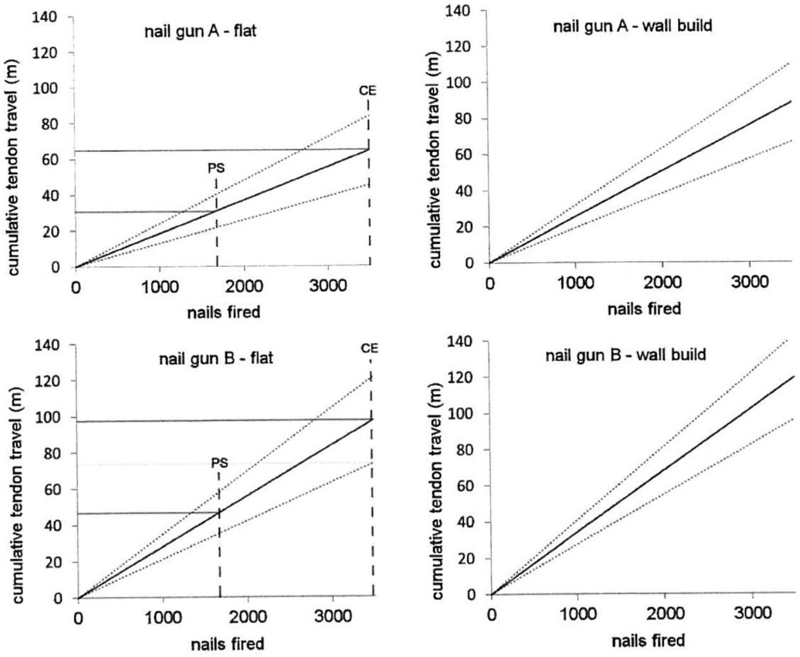

FIGURE 6.

Predicted cumulative tendon travel exposure as a function of the number of nails fired for combinations of nail gun and task (flat: flat nailing; wall build: wall building). The thin dotted lines outline the 95% confidence interval band for these predictions. Vertical dashed lines (flat nailing graphs) represent high production work estimates of nails/worker/day based on productivity standards (PS) and contractor estimate (CE), as described in the "Discussion" section.

TABLE 1

Summary of participant characteristics

Participant ID	Height (cm)	Body mass (kg)	Age (yrs)	Hand length (mm)	Palm length (mm)	Palm breadth (mm)	Index finger length (mm)	Index finger MCP thickness (mm)	Index finger PIP thickness (mm)	Index finger DIP thickness (mm)
101	175.3	83.7	51	181	103.5	84	69.5	30.5	18.5	15.0
102	182.9	77.8	50	201	119	93.5	76	30.5	19.5	16.0
103	177.8	72.4	42	187	107.5	79	74	28.0	18.5	13.5
104	172.7	81.0	69	194	111	87	74	29.0	20.0	14.5
105	180.3	90.5	49	203	107	88	77	28.5	18.0	15.0
106	190.5	81.4	30	206	104.5	89	81	26.0	18.5	14.0
mean	179.8	81.1	48.5	195.3	108.8	86.8	75.3	28.8	18.8	14.7
s.d.	6.4	6.0	12.8	9.8	5.7	4.9	3.8	1.7	0.8	0.9

Notes. MCP: metacarpophalangeal joint; PIP: proximal interphalangeal joint; DIP: distal interphalangeal joint.