Hand/Arm Forces with Pneumatic Nail Gun Actuation Systems

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A biomechanical model is presented to estimate cumulative user hand/arm force associated with two pneumatic nail gun trigger systems. The contact actuation trigger (CAT) can fire a nail when the user holds the trigger depressed first and then “bumps” the nail gun safety tip against the workpiece. With a full sequential actuation trigger (SAT) the user must press the tip against the workpiece *prior* to activating the trigger. The SAT is demonstrably safer in reducing traumatic injury risk, but increases the duration (and magnitude) of tip force exertion. Time integrated hand force was calculated for a single user from measurements of the tip contact force with the workpiece and transfer time between nails as inputs to a quasi-dynamic model of nailing in two task orientations. Application of the model shows the hand/arm force dependence upon the orientation of the workpiece in addition to the trigger system. Based on standard time allowances from work measurement systems (i.e. MTM - 1) the model results suggest that efficient application of tip contact force with the SAT would reduce total hand/arm force exertion attributable to this trigger system for this user. The present model is useful for considering differences in cumulative hand/arm force exposure between the SAT and CAT systems and the user perceptions and practices that result from these differences.

INTRODUCTION

Pneumatic nail guns (PNGs) are ubiquitous in the residential framing and building industry. The heaviest and most dangerous framing nail guns have two operating controls: (1) a finger trigger, and, (2) a workpiece contact (“safety tip”), typically spring-loaded, that must be engaged by pressing against the workpiece. PNG actuation systems can be broadly classified into two designs. The more prevalent *contact actuation trigger* (CAT) allows the workpiece contact and trigger to be activated in either order to discharge a nail and the trigger does not need to be released for individual nails. Common practice is “bump firing” in which the user holds the trigger depressed and the single action of “bumping” the workpiece safety tip against the workpiece is required to discharge each individual nail.

The sequential actuation trigger (SAT) system requires that the safety tip be pressed against the workpiece *before* the finger trigger is activated to fire a nail. Additionally, both controls must be released prior to repeating the sequence for firing of another nail. The safety benefit of the SAT is the prevention of acute trauma from unintended nail discharge.

In the period of 2001-2005 occupational use of PNGs resulted in 22,000 emergency room visits per year in the U.S. (MMWR, 2007). A surveillance study by Lipscomb et al. (2003) estimated that two-thirds of PNG injuries could have been prevented with a SAT. In spite of overwhelming evidence that the SAT is a *safer* trigger (Dement et al., 2003), use of the CAT persists (Albers et al., 2013). Significant barriers to adoption of the SAT are the perceptions of reduction in productivity and increase in physical demands from repeatedly pushing and holding the safety tip against the workpiece and depressing the trigger.

The purpose of this paper is to present a basic model to describe the user input of force for both SAT and CAT systems, in two common nailing orientations, and to estimate the difference in relative contribution of these trigger actuation systems to the total hand/arm force exerted in use of the tool.

MODEL OF NAIL GUN HAND FORCE

General Model

Hand/arm force associated with PNG use is considered based on the task elements of *holding nail gun idle* and *nailing*. The activity of *nailing* is further comprised of two task elements: *transfer between nails* and *tip contact*.

Holding nail gun idle encompasses all non-nailing aspects of manual interface with the tool. It may not necessarily represent “idleness” of the worker, but it is intended to represent idleness of the hand supporting the mass of the nail gun where the force exerted is equivalent to the weight of the tool plus 6.7 N of additional load from the air hose. Force plate measurements of standing while holding framing nail guns of approximately 35.5 N confirm a 42.2 N load. Cumulative force over the holding time is simply equal to 42.2 N multiplied by the duration of holding time. Detailed video-based time studies from field observations suggest that a range of 0.3 – 1.5 s idle holding time per nail is consistent with work practices.

Nailing - transfer between nails. In vertical nailing (Figure 1, right) hand force in the transfer of the nail gun between nailing locations was simplified by assuming that support of the nail gun mass for the duration of transfer represented the primary load in the transfer of the tool. Cumulative load was calculated by multiplying transfer time by the weight transferred.

In horizontally-oriented nailing (Figure 1, left) the external input of energy from the nail discharge and resulting recoil serves to "assist" the user in moving the nail gun away from the work piece (opposite to the gravitational vector) and creates an unloading of the tool weight from the user. In experimental testing the unloading due to recoil energy was estimated to be approximately 24% and a factor of 0.76 was applied in the calculation of cumulative force during horizontal nailing. (See Appendix Figure A.)

Nailing - tip contact. Tip contact is defined as the time between initial safety tip contact with the workpiece and the discharge of the nail, when the safety tip leaves the workpiece. The interval during which the spring is being compressed as the safety tip engages is the *spring interval*. With a CAT, the trigger is typically held depressed *before* the safety tip makes contact with the workpiece and the spring interval defines the duration of tip contact. With the SAT the user must push the tool against the workpiece sufficiently to maintain the workpiece contact in its engaged state before the trigger is depressed.

The hand force (h_{res}) of the user during the tip contact interval is dependent on the orientation of the nail gun and workpiece and was thus modeled in two workpiece orientations (See Figure 1). In flat (horizontal) nailing the nail is discharged in line with the gravity vector *requiring* less, if any, manual force by the user to engage the safety tip. (However, a tendency still exists to press with additional force against the workpiece.) Tool weight (*W*) is known and tip contact force (RF_y) was measured. Two equations (eq. 1 and 2) are needed to solve for the *x* and *y* components of hand force (h_x, h_y) as $h_z = 0$:

$$\sum M_z = (\mathrm{W} \times \mathrm{d}_1) + (h_y \times \mathrm{d}_2) - (h_x \times \mathrm{d}_3) = 0 \quad (1)$$

$$\sum F_y = RF_y - \mathrm{W} - h_y = 0 \quad (2)$$

(Distances from the nail gun mass center and grip center to the safety tip, d_i, were obtained from technical drawings of the tools.)

For vertically-oriented workpieces, representing the joining of wall studs laying on a deck surface, the tool weight makes no contribution to the force to engage the safety tip (see Figure 1, right panel). RF_x was measured, and three equations (eq. 4-6) are needed to solve for h_x, h_y, h_z:

$$\sum M_z = (\mathrm{W} \times \mathrm{d}_4) - (h_y \times \mathrm{d}_3) = 0 \quad (3)$$

$$\sum F_x = RF_x - h_x = 0 \quad (4)$$

$$\sum M_y = (h_x \times \mathrm{d}_2) - (h_z \times \mathrm{d}_3) = 0 \quad (5)$$

Resultant hand force is shown in eq. 6.

$$h_{res} = \sqrt{{h_x}^2 + {h_y}^2 + {h_z}^2} \quad (6)$$

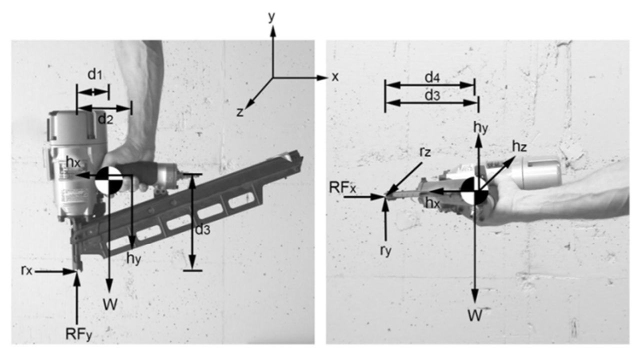

Figure 1. Static biomechanical model of nail gun forces. Horizontal nailing (left), vertical nailing (right).

METHOD

Procedure

A male carpenter (age 31 years) with 14 years experience working in homebuilding and remodeling industries was recruited to perform two nailing tasks with two nail guns using both CAT and SAT triggers. (The two nail guns had workpiece safety tip spring mechanisms with resistances of 24.4 and 37.7 N.) This individual was an experienced framing carpenter, but had minimal practice in the specific protocol and using these two specific nail guns.

The horizontal nailing (flatwork) task consisted of applying six nails in two rows spaced 40.6 cm (16 inches) apart. This mimicked the fastening of sheathing to a joist understructure as in the installation of subflooring. The vertically oriented force plate established a task representing the framing of a wall. Groups of two nail pairs were fastened into the workpiece with a 40.6 cm transfer distance between pairs - identical to that encountered when nailing studs to plates in the framing of a wall. The tasks were conducted with a horizontally-oriented and vertically-oriented biomechanics force plate (AMTI Model OR6; Watertown, MA) used to measure tip contact force. In both tasks a wooden work holding fixture was overlaid on the force plate to hold lumber over the plate surface.

Data Analysis

Cumulative, or time integrated, hand force was calculated for three conditions: CAT, $SAT_{measured}$, and $SAT_{predicted}$. The CAT and $SAT_{measured}$ conditions were the performance of the carpenter. $SAT_{predicted}$ was based on assumptions for a theoretically "efficient" performance derived from MTM-1 (Methods-Time Measurement) using standard time allowances for the *application of force* (including *apply force* and *dwell* times) and a 72 ms allowance for a *basic finger motion* (Barnes, 1980). These represent the phases of pressing the safety tip against the workpiece and trigger activation, respectively. The *magnitude* of the $SAT_{predicted}$ force was based on a tip contact force level that provided a 25% buffer above the measured spring resistance force. The MTM-1 time allowance assumptions are shown in Figure 2.

Estimates of cumulative hand force were calculated per nail fired (Lowe et al., 2013). These were based on discrete integration of resultant hand force in the measured tip contact interval (performed with LabVIEW v8.1; National Instruments; Austin, TX). For *holding nail gun idle* the cumulative hand force was the hold duration multiplied by tool weight. In the transfer phase the calculation was similar with the factor of 0.76 (reduction due to recoil energy) applied in the horizontal nailing orientation. (Appendix Figure A.)

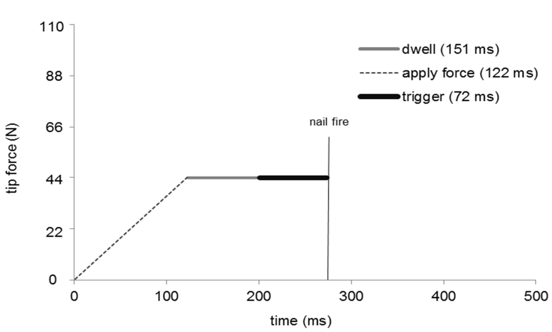

Figure 2. *Predicted* force-time history ($SAT_{predicted}$) for tip contact interval. Based on MTM-1 allowances for apply force, dwell, and finger motion to activate trigger.

RESULTS

Figure 3 shows an ensemble average hand force during tip contact for 12 nails fired (vertical orientation, SAT nail gun). The measured tip contact force, h_x, is plotted with the calculated h_y, h_z, and resultant (h_{res}) hand force. Cumulative hand force in the tip contact interval is calculated as the integrated area under the resultant hand force time history.

Figure 4 shows the total cumulative hand force per nail as the sum of cumulative hand forces for tip contact (blue), transfer (red), and idle holding of the nail gun (hatched region). The contribution of idle holding, dependent on idle holding *time,* is shown over a range of 0 to 2 s time per nail, represented by the height of the hatched portion of the bar.

Hand force for the carpenter during tip contact is negligible for the CAT in horizontal nailing (Figure 4, rightmost bar pair, left bar) because the weight of the nail gun exceeds the safety tip spring resistance. In the vertical nailing condition with CAT the carpenter's hand force during tip contact contributes slightly to the user's total cumulative hand force (ranging from 5% for 0 s idle hold time to 2% for 2 s idle hold time per nail).

This contrasts with the carpenter's hand force using SAT ($SAT_{measured}$) which during tip contact made up as much 40% (0 s/nail idle hold time) to as little as 18% (2 s/nail idle hold time) of the total force in horizontal nailing and 45% to 24% in the vertical orientation nailing. (See Figure 4, leftmost bar pair)

For $SAT_{predicted}$, (Figure 4 middle pair of bars), the hand force during tip contact was between 8% and 2% of total force, depending on idle hold time (0 – 2 s per nail) in horizontal nailing and between 20%-9% in the vertical. This performance would reduce hand force *in the tip contact phase* exhibited by the carpenter using SAT by 70% and 88%, for horizontal and vertical orientations respectively.

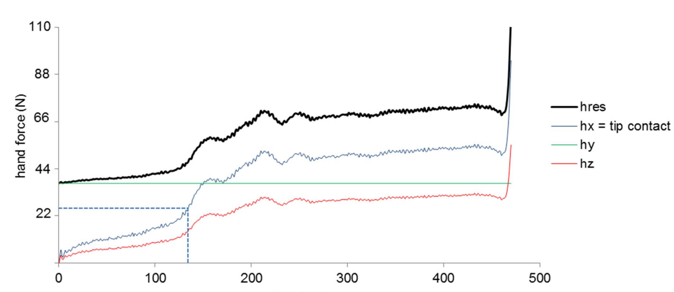

Figure 3. *Measured* force-time history ($SAT_{measured}$) for tip contact interval. h_x measured on force plate, h_y, h_z, and h_{res} calculated from equations 3-6. Dashed blue line represents spring interval (time to overcome 24.4 N spring resistance).

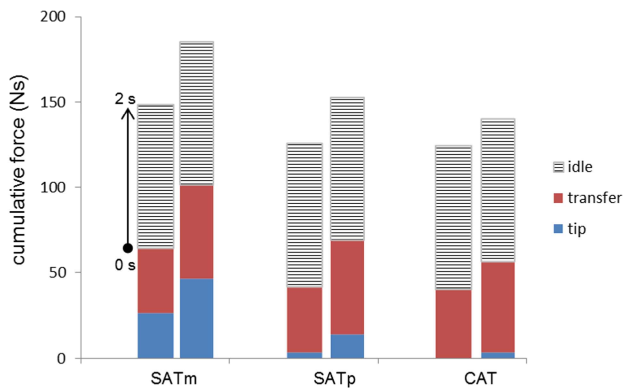

Figure 4. Cumulative (integrated) hand/arm force for $SAT_{measured}$, $SAT_{predicted}$, and CAT. Pairs of bars represent horizontal (left) and vertical (right) nailing orientations. The hatched portion of the bars represent a range in idle holding time from 0 to 2 s per nail.

DISCUSSION

This assessment considered the transfer of force to the PNG when supporting its mass and when pressing the safety tip against the workpiece to fire a nail. Higher levels of hand/arm force per nail fired were expected with the SAT, and the analysis confirms this. Informal testing with a practiced nail gun user (not reported) confirmed that the performance predicted by MTM-1 time allowances ($SAT_{predicted}$) is achievable with practice - particularly the trigger interval time. Furthermore, Radwin and Yen (1998) reported an SAT trigger time of 60 ms for experienced nail gun operators – 17% *less* than the time predicted in this analysis.

A limitation of the present analysis is that it was simplified by assuming independent, discrete phases of nail gun use: idle holding, transfer, and tip contact. The quasi-dynamic analysis largely disregarded inertial effects in the transference of force to the safety tip *after* workpiece contact (though recoil inertial effects were represented in the transfer phase). A second limitation of this analysis is that it did not account for posture of the upper limb and the coupling (grip) of the hand with the nail gun. Transference of arm force with the wrist in non-neutral postures (as we have observed) would increase activation of the wrist stabilizing muscles and increase internal stress on tendons and soft tissues spanning the wrist.

In spite of the above limitations, there are PNG use consideration that can be better understood in the context of this analysis.

Removal of spring resistance in the safety tip. This is NOT recommended under ANY circumstances. However, this practice may have the perceived benefit of reducing the force exertion of the user. In the vertical nailing orientation, where the tool mass does not contribute to displacing the spring, the user must manually exert this force. Springs in framing nail guns typically require 19.5 – 43.9 N of force to engage the workpiece contact (CPSC, 2002). Eliminating this resistance in the tip may be perceived to reduce exertion and fatigue over hundreds, or thousands, of repetitions over longer periods of use of the nail gun.

Skill and experience related to trigger choice. "Bump" firing with a CAT removes the need to hold the safety tip pressed against the workpiece preceding and during trigger activation. The trigger is simply held depressed statically in the grip and the safety tip then acts as *a single operating control*. This serves to limit tip force in duration and magnitude and reduces the cumulative manual force the user must exert over a longer work period when many nails are fired. The SAT system has no mechanism which "limits" tip force in duration or magnitude. This is determined by user control. Thus, in terms of reducing manual force and musculoskeletal response, improving efficiency of technique may have more benefit with SAT use. The present analysis suggests that more efficient coordination of tip contact force and trigger activation might reduce differences in cumulative musculoskeletal load between SAT and CAT.

Relationship with productivity. The present analysis did not account for the effect of trigger system on transfer time between nails. Estimates of the advantage of CAT in *nailing speed* vary - ranging from a 50% difference reported for a high production manufacturing task (Radwin and Yen, 1998) to a difference of only 10% in a residential construction framing application (Lipscomb et al., 2008). Regardless, the effect of nailing speed on overall construction *project completion time* is dependent on a multitude of factors. Lipscomb et al (2008) noted that the 10% increase in nailing speed with CAT resulted in only 0.77% decrease in project completion time when considering all nailing and non-nailing activities. This is a truer measure of construction productivity. Even if the acquisition of skill reduced transfer time of the nail gun the effect of the faster nailing on musculoskeletal disorder risk is unclear. This contrasts with the clear reduction of hand/arm force exertion when tip force is more efficiently applied.

CONCLUSION

The present model represents a framework through which hand/arm force transmitted to the nail gun, and differences between SAT and CAT, can be conceptualized. Performance data from one framing carpenter suggests that the additional force to push the nail gun safety tip against the workpiece prior to and during trigger activation of the SAT may be reduced as this user more efficiently controls the input of force to the safety tip with the SAT system. Additional studies are needed to improve understanding of how the acquisition of skill with the SAT may offset the perceived advantage of the CAT in reducing hand/arm force. This knowledge should be combined with that of finger tendon motion associated with repetitive triggering of SAT (Lowe et al., 2013) and future work needed to assess differences in finger tendon forces. Decisions regarding use of the higher risk (traumatic injury) CAT system to reduce hand/arm exertion should consider the significance of that reduction in the context of the *total* nail gun hand/arm force, independent of actuation system.

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

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APPENDIX

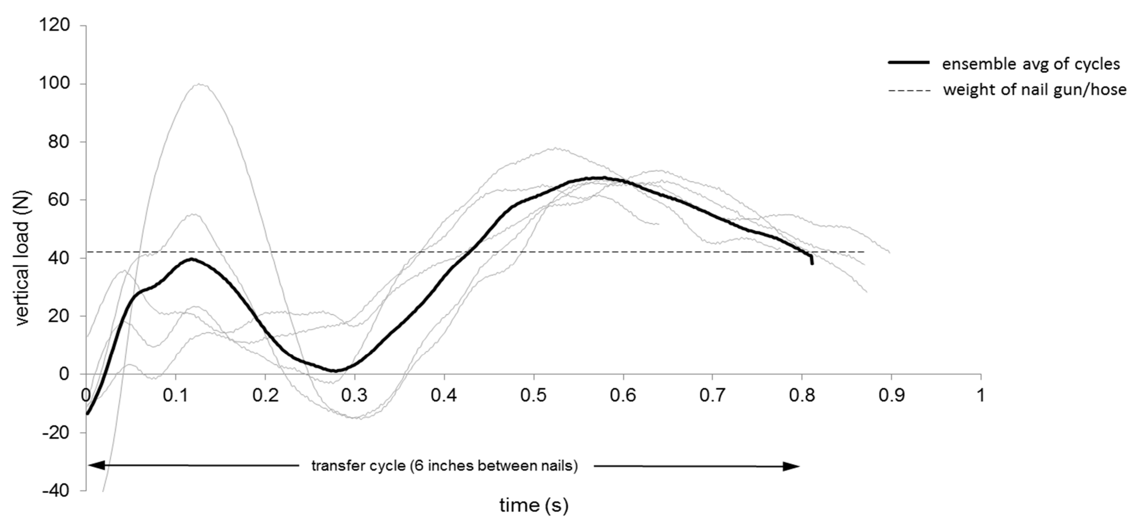

Figure A. Experimental determination of unloading in the transfer of the nail gun due to recoil energy (horizontal nailing). Traces show five individual cycles and the ensemble average (dark line) of the ground reaction force (minus the user's body weight) measured under the nail gun user. A cycle is measured from nail fire to the tip contact at the next nail placement. The static weight of the tool (42.2 N) is the horizontal dashed line and the integrated area under the dark solid trace is 76% of that under the dashed line.