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A Biomechanical Assessment of Hand/Arm Force with Pneumatic Nail Gun Actuation Systems

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Abstract

A biomechanical model is presented, and combined with measurements of tip press force, to estimate total user hand 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 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 (cumulative) 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 static model of the nail gun and workpiece in two nailing task orientations. The model shows the hand 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. Methods-Time Measurement - 1) it is proposed that efficient application of hand force with the SAT in maintaining tip contact can reduce force exertion attributable to the sequential actuation trigger to 2–8% (horizontal nailing) and 9–20% (vertical nailing) of the total hand/arm force. The present model is useful for considering differences in cumulative hand/arm force exposure between the SAT and CAT systems and may explain the appeal of the CAT trigger in reducing the user's perception of muscular effort.

Keywords

nail gun; ergonomics; fatigue

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BACKGROUND

In the period of 2001–2005 occupational use of pneumatic nail guns resulted in 22,000 emergency room visits per year in the U.S. (MMWR, 2007). Approximately two-thirds of these traumatic injuries were to the upper extremities, hand, and fingers (MMWR, 2007) and were relatively minor in terms of treatment, outcomes, and lost time. However, more serious injuries, and even fatalities, have been reported (CPSC, 2002a). The ubiquitous use of the framing nail gun (which discharges a larger fastener) in the residential construction trade, and the increasing prevalence of their use among consumers make these larger framing nail guns of greatest concern in this class of tools.

In addition to a finger trigger, pneumatic nail guns (PNGs) for wood framing have a second operating control consisting of a spring-loaded work piece contact ("safety tip") that must physically engage by pressing against the workpiece. This safety tip prevents a nail from acting as an airborne projectile. PNG actuation systems can be broadly classified into two designs based on whether the controls must be operated in a sequence-dependent order. The contact actuation trigger (CAT) design allows the workpiece contact (safety tip) 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 with the CAT is "bump firing" in which the user holds the trigger depressed and only the single action of "bumping" (pressing) the workpiece safety tip against the workpiece is required to discharge an individual nail. The safety concerns with such a design have been well documented (Lipscomb et al., 2003, 2008a). When the trigger is held depressed an inadvertent "bump" against the workpiece contact of the tool can, and often does, discharge a nail.

The full sequential actuation trigger (SAT) design requires a sequence-dependent activation of the controls. The safety tip must be pressed against the workpiece *before* the finger trigger is activated to discharge a nail. Additionally, both controls must be released prior to repeating the sequence for firing of another nail. The safety benefit of the SAT design is the prevention of trauma due to unintended nail discharge and the prevention of double fire, where the nail gun recoil results in an inadvertent second contact with the tip against the workpiece.

A common perception in the residential construction industry is that CAT PNGs increase productivity and result in "easier" use than SAT PNGs. In spite of the fact that the SAT is a demonstrably *safer* trigger, (Lipscomb, et al., 2003; 2008a) significant barriers to adoption of the SAT appear to be the perceived reduction in productivity and the perceived increase in physical demands of the SAT because of the two-stage process of engaging the safety tip followed by trigger press.

The purpose of this paper is to present a basic model to describe the user input of force required by both SAT and CAT systems, in two common nailing orientations, and to estimate the differences in relative contribution of these trigger actuation systems to the total hand force exerted in use of the tool. The model simplifies nail gun use to a basic mechanical system with external forces acting on the nail gun to support the mass of the tool when held idly and to apply force on the workpiece contact (safety tip) to actuate the tool.

The dynamics associated with movement of the nail gun throughout the workspace are simplified in the model because there are countless nuances in work practice and user technique affecting the dynamics of the PNG as it is transferred into position prior to making tip contact with the workpiece. The model does account for the effect of recoil energy unloading the mass of the tool supported by the user in the transfer of the nail gun between nail locations in repetitive nailing on a horizontal workpiece (e.g. sheathing).

MODEL OF HAND FORCE ON THE NAIL GUN

2.1 General Model

Hand force associated with PNG use is considered in the framework shown in Figure 1. Exertion of force results from the *holding nail gun idle* and *nailing* task elements. Other activities in residential construction that do not involve interface with the nail gun, are not considered. The activity of *nailing* is comprised of two task elements: *tip contact*, the action of discharging a nail while the safety tip of the nail gun is pressed against the workpiece, and *transfer between nails*, the action of moving the nail gun to the next nail location during which time there is no contact between the nail gun and workpiece and the mass of the PNG is supported by the user. *Holding nail gun idle* encompasses all other 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. In a time and motion study context this could be considered an “unavoidable delay” for the hand holding the nail gun, while the opposite hand is positioning another object, such as a workpiece. It could also represent both hands being inactive if the worker is walking between locations on the worksite, but not in the process of nailing (also unavoidable delay). Finally, the nail gun can be held idly by the worker in an avoidable delay situation.

Holding Nail Gun Idle—When *holding nail gun idle* it is assumed that the exertion of hand force by the user is equivalent to the tool weight 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 in weight, half-filled with nails, connected to a supply hose confirm a 42.2 N load. Cumulative force over the holding time is simply equal to the weight of the nail gun and hose (42.2 N) multiplied by the duration of holding time. The activity of loading the nail gun is considered *holding the gun idle* because the primary exertion is to support the tool weight. When holding the nail gun idle exertion by the user is assumed to be independent of the actuation system. Estimates for idle nail gun holding time per nail fired are presented in Appendix A and suggest that a range of 0.3 – 1.5 s idle holding time per nail is consistent with work practices.

Transfer of Nail Gun Between Nails—Hand force in the transfer of the nail gun between nailing locations was simplified by assuming that support of the nail gun mass against gravity for the duration of transfer represented the primary load in the transfer of the tool. Cumulative load could then be calculated by multiplying transfer time by the weight transferred. We differentiated between movement of the nail gun with a vertically-oriented workpiece and horizontally-oriented workpiece (flat nailing), because in the latter orientation the external input of energy from the nail fire 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. For nailing a vertically oriented workpiece (such as "through-nailing" studs to plates in the framing of a wall) the recoil of the nail gun is directionally perpendicular to the gravity vector and makes no contribution to unloading the mass of the tool supported by the user. The reduction in load due to recoil energy was estimated in experimental pilot testing (described in Appendix B) and applied in the calculation of cumulative hand force during nail gun transfer in horizontal (flat) nailing.

Tip Contact—*For* each fired nail tip contact is defined as the time between initial safety tip contact with the workpiece and ends with nail fire, when the recoil energy moves the safety tip off the workpiece. (Figure 2.) Hand force applied to the nail gun overcomes the resistance in the safety tip mechanism, which includes a spring-loaded sliding workpiece contact. The interval during which the spring is being compressed before the safety tip engages is referred to as the *spring interval*. With a CAT, the trigger can be held depressed *before* the safety tip makes contact with the workpiece and the nail gun discharges a nail at the instant the spring resistance is overcome. With the full sequential actuation trigger (SAT) the trigger must be activated *after* the spring interval and the nail gun discharges a nail at the instant the trigger is activated. The duration of tip contact with the SAT thus includes the spring interval and a latency associated with a *trigger interval*. The trigger interval is the duration of time during which hand force is applied to push the safety tip against the workpiece as the trigger is activated by the finger(s). With the SAT the user must push the tool against the workpiece with a force sufficient to maintain the workpiece contact in its engaged state as the trigger is being depressed. There is no *upper* limit to the force, in duration or magnitude, with which the user applies force against the workpiece prior to the trigger actuation.

2.2 Calculation of Hand Force

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. In flat (horizontal) nailing the nail is discharged in line with the gravity vector (see Figure 3a), and this requires less, if any, manual force by the user to engage the safety tip because the weight of the nail gun overcomes a significant portion, if not all, of the spring resistance. 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) because no force is required in the z axis:

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

$$\sum F_y = RF_y - \mathrm{W} - h_y = 0 \quad \text{eq. 2}$$

The resultant hand force is simply that in eq. 3.

$$h_{res}=\sqrt{{h_x}^2+{h_y}^2} \quad \text{eq. 3}$$

(Distances from the nail gun mass center and grip center to the workpiece safety tip (d_i) were obtained from scaled technical drawings of the tools and knowledge of the tool centers of mass.)

When nailing a vertically-oriented workpiece (see Figure 3b) as commonly seen in the framing of a wall or partition laying on the floor level, the tool weight makes no contribution to the required manual application of force to engage the safety tip (see Figure 3b). In this case the user must support the weight of the tool against gravity while pressing the tool horizontally against the workpiece. *W* is known, RF_x is measured, and three equations (eq. 4–6) are needed to solve for h_x, h_y, h_z:

$$\sum M_z=(\mathrm{W}\times \mathrm{d}_4)-(h_y\times \mathrm{d}_3)=0 \quad \text{eq. 4}$$

$$\Sigma F_x=RF_x-h_x=0 \quad \text{eq. 5}$$

$$\sum M_y=(h_x\times \mathrm{d}_2)-(h_z\times \mathrm{d}_3)=0 \quad \text{eq. 6}$$

With resultant hand force in eq. 7.

$$h_{res}=\sqrt{{h_x}^2+{h_y}^2+{h_z}^2} \quad \text{eq. 7}$$

In calculating resultant hand force in the horizontal workpiece condition the vertical y component of hand force during the spring interval ($h_{yspring}$) was forced to zero because it was assumed that the user does not exert decelerative force in opposition to the inertial acceleration of the nail gun as the spring is compressed. Inertial forces were ignored during the tip contact interval and hand force was calculated as the integrated resultant hand force from the static biomechanical model shown in Figure 3.

2.3 Cumulative Hand Force in Representative Framing Tasks

Cumulative, or time integrated, hand force ($h_{cumulative}$) was calculated for one condition with the CAT and two conditions with the SAT (SAT conditions 1 and 2). The CAT condition and SAT condition 1 were the measured performance of a single. SAT condition 2 was based on assumptions for more “efficient” performance with SAT in which the tip contact interval and tip force magnitude were reduced to levels consistent with standardized work measurement systems. Efficient application of tip force involves the coordination of the applied push force to activate the safety tip with the subsequent trigger activation – the net effect of this coordination being a reduced tip contact interval. Assumptions for efficient application of force and trigger actuation were derived from MTM-1 (Methods-Time Measurement) standard time allowances for the application of force 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 more efficient force was based on a target tip contact force level that provided a 25% buffer above the measured spring resistance force. The MTM-1 time allowance assumptions, and time histories of tip contact force based on these assumptions, are shown in Appendix C. The push force requirement against the workpiece is only that needed to compress the spring loaded safety mechanism. In reality, users tend to apply more force than necessary – significantly greater than a 25% increase over the spring resistance force.

Estimates of cumulative hand force, $h_{cumulative}$, were calculated per nail fired, and thus scalable to production output (Lowe et al., 2013) based on equationss 8 and 9, for vertical and horizontal orientations, respectively.

$$h_{cumulative}=(\mathrm{t}_{idle\ hold} \times \mathrm{W})+(\mathrm{t}_{transfer} \times \mathrm{W})+\int_t h_{tip\ contact}dt \quad \text{eq. 8}$$

$$h_{cumulative}=(\mathrm{t}_{idle\ hold} \times \mathrm{W})+(\mathrm{t}_{transfer} \times \mathrm{W} \times 0.76)+\int_t h_{tip\ contact}dt \quad \text{eq. 9}$$

In the equations, $ti_{dle\ hold}$ is the average idle hold time, $t_{transfer}$ is the average transfer time, and W is the tool weight. The factor 0.76 reflects a reduction in cumulative load due to recoil energy when nailing in the horizontal orientation (see Appendix B.) Discrete integration of resultant hand force in the measured tip contact interval was performed with LabVIEW v8.0 (National Instruments; Austin, TX).

A male carpenter (age 31 years) with 14 years experience working in the residential framing and remodeling industries was recruited to perform two nailing tasks with two nail guns using both CAT and SAT triggers. This individual was an experienced user of nail guns in the framing carpentry trade, but had minimal practice in the specific protocol and using these two specific nail guns. 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 surface to hold pieces of lumber over the plate surface. Force in the axis normal to the force plates from the mass of the work holding fixtures was subtracted from measurement as a zero offset.

The two nail guns had workpiece safety tip spring mechanisms with different resistances. The spring resistances were measured as having approximately 24.4 and 37.7 N force to fully compress (measured with Chatillon DF series force dynamometer; AMETEK Largo, FL).

The horizontal nailing (flatwork) task consisted of applying six nails in two rows spaced 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 16 inch transfer distance between pairs - identical to that encountered when nailing studs to plates in the framing of a wall.

MODEL RESULTS

Figure 4 shows an example of calculated hand force during tip contact in a trial (vertical orientation, SAT nail gun). The measured tip contact force (equivalent to the×component of hand force, h_x) is plotted with the calculated h_y, h_z, and resultant (h_{res}) hand force. The time history shown represents an ensemble average for 12 nails fired in the trial. The spring interval and trigger intervals are defined by the time when the tip contact force achieved the spring resistance level measured for the nail gun. Cumulative hand force in the tip contact interval is calculated as the integrated area under the resultant hand force time history.

Figure 5 shows the cumulative hand force (per nail) in the tip contact interval as a function of nailing orientation for two different nail guns for the participant. The pairs of bars represent the two nail guns tested. Cumulative hand force is shown differentiated by that in the spring and trigger interval.

Figure 6 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). These totals are shown over a range of 0 to 2 s idle holding time per nail, represented by the height of the hatched portion of the bar.

Hand force during tip contact is negligible for the CAT in the horizontal nailing condition because the weight of the nail gun exceeds the spring resistance in the safety tip. A small x-component of hand force counteracts the moment of the tool about the tip, so the resultant hand force is non-zero, but is not visually discernible in the Figure 5 and 6 graphs. In the vertical nailing condition with the CAT hand force during the tip contact interval contributes slightly to the total cumulative hand force (see Figure 6, rightmost bar). The cumulative hand force is low because the tip contact duration is short and the CAT mechanism prevents any static application of force in excess of the spring resistance. As a result, hand force during tip contact accounted for at most 5% and perhaps as little as 2% of the user's estimated *total* hand force in vertical nailing with the CAT. (5% of total force if idle hold time were 0 s per nail, 2% for idle hold time of 2 s per nail.)

This contrasts with the SAT - condition 1 (see Figure 6) in which the user's hand force for maintaining tip contact made up as much as 45% (0 idle hold time), down to 24% (2 s per nail idle hold time) of the estimated total hand force in the vertical orientation. Under the assumptions of condition 2 (efficient use based on MTM time allowances) the hand force in tip contact was between 20% and 9% of total force, depending on idle hold time assumption (0 – 2 s per nail). For the SAT trigger, if the MTM-1 time allowances and efficient force estimates are achievable the hand force *in the tip contact phase* exhibited by the individual participant could be reduced by 70% and 88%, for horizontal and vertical orientations respectively. Hand force during tip contact was 93% and 99% less for the unpracticed user when using CAT relative to SAT in the horizontal and vertical orientation, respectively. The more important consideration, however, is the percentage reduction in *total* hand force which includes force applied to maintain tip contact and the more significant duration of supporting the tool weight in transfer and holding. Assuming an idle hold time of 0.4 s/nail (which is consistent with our field observations) this would amount to a 28% and 27%

decrease (horizontal and vertical orientations, respectively) in total hand force between SAT – condition 2 and SAT – condition 1. By comparison, the CAT condition resulted in a 30% and 38% reduction from the SAT- condition 1 in horizontal and vertical orientations, respectively.

4. DISCUSSION

Reducing hand force is desirable in preventing fatigue, discomfort, or musculoskeletal symptoms attributable to use of a tool. This analysis operationalized hand force as the time integral of the resultant force exerted on the nail gun by the user, normalized per nail. Force requirements in the use of the tool were estimated based on its weight and the forces associated with its actuation. By characterizing cumulative hand force at the unit of the single nail fired, estimates are derived that could be scaled to production output (Lowe et al., 2013). Higher levels of hand force per nail fired were expected with the SAT. The two-stage sequence of pressing the safety tip with sufficient force against the workpiece and maintaining this force while activating the trigger increases hand/arm force exertion (in duration and in magnitude) beyond that needed to actuate the CAT system. Informal testing with a practiced nail gun user (who, unlike the present study participant, had no occupational experience in the construction industry) confirmed that the performance predicted by MTM-1 time allowances is achievable with practice - particularly the trigger interval duration. Furthermore, Radwin and Yen (1998) reported an SAT trigger time that averaged approximately 60 ms for experienced nail gun operators in a manufactured housing production facility – a 17% reduction in trigger activation time from the 72 ms assumed in the present study based on MTM-1 time allowances.

The present analysis was based on measurement of the active input of force by the user to engage the workpiece safety tip for firing nails. The tip contact forces were measured during simulations of two common framing tasks with the nail gun in horizontal and vertical firing orientations. The tasks were realistic spatial representations of the orientation of the nail gun in the application of just a few nails in close proximity – constrained to the surface area of a 0.46 m × 0.51 m force plate. However, the data were collected in a controlled environment, which did not account many of the work pace characteristics or larger scale spatial characteristics of the workspace that exist on a real job site.

Using a static model, calculation of hand force was straightforward in the tip contact interval based on the measured tip force and the tool weight. When the user is holding the nail gun idle, the weight of the tool is the sole determinant of external load, and the external hand force is also straightforward. The model is less robust in its characterization of hand force in the transfer of the tool in the workspace. The analysis largely neglected inertial effects on the hand force requirements. By applying an experimentally-derived factor, applicable in the horizontal nailing orientation, the model accounted for the advantageous effect of recoil energy input after nail fire that reduces load the user must support during rhythmic patterned transfer of the nail gun.

A limitation of the analysis is that it was simplified by considering discrete phases of nail gun use: transfer, tip contact, and (when applicable) trigger actuation. Interpretation of cumulative loads in this simple additive representation of three defined phases may not necessarily reflect internal soft tissue response and resulting musculoskeletal risk.

A second limitation of this analysis is that it considers only external hand force transmitted to the tool in supporting its mass and pushing it against the workpiece for each fired nail. The effect of repetitive hand/arm force on the musculoskeletal system can not be assessed without accounting for posture of the upper limb and the coupling (grip) of the hand with the nail gun. The grip/finger interface forces on the tool are not considered and the model does not translate the grip forces into predicted internal stress on the soft tissues or to user fatigue. Grip of the nail gun to apply hand forces as described creates moments about the finger and wrist joints and internal tendon forces that can be predicted only by more sophisticated biomechanical modeling approaches. While not measured in this study, observations of framing work suggest significant wrist flexion and deviation, particularly in wall building tasks (the vertical condition in this study) in which studs are nailed to plates on the ground level. Transference of arm force with the wrist in these non-neutral postures would increase activation of the wrist stabilizing muscles and increase internal stress on tendons and soft tissues spanning the wrist. Flat nailing at ground level appears to create less non-neutral wrist posture, so an equivalent arm force may create less upper limb internal tissue stress. However, flat nailing is typically done at ground level, requiring a stooped posture, and this type of work has been associated with back injury risk. Extended periods of stooped posture for nailing at ground level are at odds with recommendations for reducing flexed trunk posture and may create transference of risk to the low back (Mirka et al., 2003).

In spite of these limitations it is believed that this analysis offers a framework whereby the physical demands of the sequential actuation trigger and the contact actuation trigger can be compared and tool design, work practice, and administrative approaches to reducing traumatic injury risks and musculoskeletal loads can be considered. There are several issues related to work practices and administrative policies that can be considered in the context of this analysis:

Removal of Spring

In focus group discussions residential home builders have described a practice that involves removal of the spring from the workpiece contact safety tip. This practice is contrary to that given by nail gun manufacturers' safety materials and other guidelines on safe nail gun use. While not recommended from a safety standpoint, the perceived benefit of the spring removal can be understood in the context of the present model. For each nail fired the user must apply manual force to overcome resistance in the spring to engage the safety tip workpiece contact. 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, 2002b). The effect of eliminating this resistance in the tip reduces the required tip contact force and may be perceived to reduce exertion and fatigue over hundreds, if not thousands, of repetitions over longer periods of use of the nail gun.

The effect of this behavior can be considered in the context of regulations for powder actuated nail guns. Powder actuated tools (PATs) have more risk than pneumatic tools due to their much higher exit velocity. PAT regulations require that "The tool must not be able to operate until it is pressed against the work surface with a force of at least 5 pounds (2.2 kg) greater than the total weight of the tool." (OSHA, 2002). This requirement is intended to prevent a design in which the tool mass is sufficient to overcome resistance in the workpiece contact. Safety is enhanced by requiring the user to exert press force against the work surface – exactly the opposite effect to the removal of the spring in a pneumatic nail gun.

Restriction of CAT to "Experienced" Users

"Bump" firing with a CAT removes the need to coordinate a finger motion on the trigger with application force at the workpiece contact. The trigger is simply held depressed and the nail gun fires when the tip force exceeds the resistance of the internal spring. This serves, in effect, as an upper bound on the application of high force. The SAT mechanism has no upper limit on the tip force that can be applied prior to trigger actuation. In terms of reducing musculoskeletal effort, the acquisition of skill, specifically the more efficient temporal coordination of trigger activation with the target tip contact force, may have more potential benefit for the user of the SAT. As an unskilled user gains skill with the SAT it can be hypothesized that performance will become more efficient, thus reducing disparities between the trigger systems with regard to the exertion of hand force.

Relation to Productivity

Estimates of the advantage of CAT in terms of nailing productivity vary widely. Radwin and Yen (1998) reported a nailing rate with CAT that was almost double that of SAT in a controlled nailing task representative of nail gun use in the manufactured home production industry. The application in their study was particularly conducive to high nailing speed. In the construction of small framed sheds (a task representative of residential framing work in the construction industry) Lipscomb et al. (2008) reported only a 10% increase in nailing time with the SAT relative to CAT. The net effect on total project completion time, a truer measure of productivity, was only 0.77%. It can be concluded that *nailing speed* is faster with the CAT, however, the net effect on *total productivity* is smaller, and dependent upon the percentage of the total project time consumed by nailing. For the occupational user of these tools improved productivity does not necessarily translate to reduced musculoskeletal load. In fact, the opposite could be the case. While this can not be concluded with certainty, the reduction in total cumulative hand force per nail fired with the CAT may be less than 10% for an efficient user of the SAT. (The present data, for a single subject indicated decreases of 3% in the horizontal and 15% in the vertical orientations). If so, then the increase in nailing output potential by the CAT is not offset by an equivalent reduction in hand force per unit output. Conceivably, this could *increase* cumulative hand force exposure with CAT for an occupational user if nailing work *time* was unchanged. We have observed crew organizations based on task specialization in which one or more carpenters are dedicated exclusively to nailing. Crew member dedicated to nailing of materials may spend over 70% of the work time with the nail gun in hand. Increased nailing speed for these workers equates to increased output and, potentially, increased cumulative hand force. Reducing hand force exposure per unit output does not benefit the worker if an increase in output more than offsets the reduction.

Skill and Experience

Lipscomb et al. (2008b) noted that more of the variance in nailing speed and productivity was attributable to the nail gun user than to the nail gun trigger system, but that years experience in the carpentry trade was not a significant predictor of productivity. These findings were for project completion time and imply that *skill* may not be adequately proxied by years *experience*, at least insofar as skill is associated with increased productivity. While confirmatory work is needed, the present analysis suggests that “skill”, if defined by more efficient coordination of tip contact force with trigger activation, would also be a determinant of hand force and musculoskeletal load. Conducting research to confirm this hypothesis has risks, however, because the ideal study design would include skilled and unskilled users of both trigger systems, and the safety risks (for traumatic injury) associated with these tools are a significant concern - particularly with unskilled users of the CAT.

The present analysis did not account for the possibility of skill acquisition affecting a reduction in transfer time between nails. This reduction in transfer time (increased nailing speed) has clear implications on increasing *productivity*, but the effect on musculoskeletal loading is less clear. Reducing the duration of the transfer phase, where the constant tool weight and movement distance result in no change in mechanical work performed, would not reduce exertion to the same extent as reducing the duration of static application of tip contact force against the workpiece. As described above, as a user becomes more skilled and nails faster, the workload associated with transfer of the nail gun may increase due to an increase in nailing volume. From a traumatic injury risk perspective, faster nailing places the user at greater risk for injury.

Recommendations from a number of governmental safety organizations have advised the use of the full SAT in construction work (Safe Work South Australia, 2007; New Zealand OSH, 2001; DHHS/NIOSH, 2011) – a recommendation motivated by traumatic injury risk and safety considerations. These recommendations have, to some extent, also considered “overuse” injury potential and, in that context, have differentiated nail gun use in the Construction Industry from that in high-volume manufacturing of standard products such as wooden pallets (New Zealand OSH, 2001). Some contractors have adopted work practices that compromise by restricting the use of CAT to flat nailing (sheathing, roofing, and subflooring applications) when a work piece is not held in the opposite hand.

The present model suggests that the additional hand force to push the nail gun safety tip against the workpiece during trigger activation of the SAT may be reduced as a user gains skill with this trigger system. Arguments *against* use of the SAT based on assertions of increased hand/arm force should consider the magnitude of this additional force in the context of total hand/arm force of nail gun use. Additional work is needed to improve understanding of how the acquisition of skill with the SAT may offset a perceived advantage of the CAT in reducing hand/arm force. If the relative advantages of the CAT decrease as users become more skilled with SAT, the case for the use of the SAT to gain its clear benefit in reducing traumatic injury risk can be made even stronger.

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APPENDIX A

Determination of Nail Gun Idle Holding Time

Nail gun *idle holding time* was estimated per nail fired to be scalable to production output. The estimate for typical idle holding time was derived from a video-based observational time-study of tasks in three framing projects with three carpenters within non-unionized crews. The three video segments of framing work were observed and analyzed using the

MVTA - Multimedia Video Task Analysis System (Yen and Radwin, 1995). Intervals of nail gun holding were coded on the timeline by marking the video frame in which the user set down or picked up the nail gun – transitions to/from holding the nail gun that were clearly discernible events. Total nail gun hold time for the video segment was the sum of all durations of nail gun holding intervals. The number of nails fired by the worker during the video segment was also counted.

Total nail gun holding time was divided by the number of nails fired in the video segment. The resulting values for average nail gun holding time per nail fired ranged from 0.64 – 4.95 sec (see Table A1). The trim work task involved more extensive placement and positioning of materials from a roof and is believed to represent an extreme. For most tasks the idle hold time/nail is believed to be in the 0.6 to 1.8 sec range. Since the nail gun holding time includes the *transfer time* and *tip contact time*, the *idle* holding component is calculated by subtracting these values. Typical *idle* hold times are thus assumed to be in the range of 0.3 – 1.5 sec/nail. Figure 6 shows cumulative hand load over the range of 0 to 2 s of idle hold time per nail.

Table A1

Results of time-study determination of nail gun holding time per nail fired.

video	description	observation time (s)	nail gun hold time (s)	% time holding nail gun	nails fired	hold time/nail (s)
1	trim work	638	247.4	39	50	4.95
2	multi-family structure - rapid wall building (joining of studs to plates, headers, sills, etc.)	1491	1060.1	71	879	1.21
3	multi family subflooring application (flatwork). Rapid nail application with short, linear transfer of nail gun between nails	371	258.7	70	405	0.64

APPENDIX B

Evaluation of the Effect of Recoil Energy in Unloading Nail Gun Transfer

In horizontal nailing, where the nail gun recoil is directed vertically in opposition to the gravity vector, the recoil energy input assists the user by unloading the weight of the tool that would otherwise be supported by the user. The contribution of recoil energy in flat nailing was assessed by simultaneous measurement of independent ground reaction force (GRF) under two force plates – one under the standing user and one under the workpiece. GRFs were measured for two subjects while flat nailing in a manner similar to a sheathing or subflooring application – where the distance between nails was 6 or 16 inches. The vertical GRF under the standing subject (measured on force plate 1) was characterized during the transfer phase of the nail gun, defined as the interval in which the nail gun tip was not in contact with the workpiece (corresponding to a GRF of zero on force plate 2). Individual cycles of nail gun transfer were defined from force-time history on force plate 2 – the interval from nail fire to the initiation of tip contact for the subsequent nail. The calculation of the unloading on the user was made from the GRF measured on force plate 1 during that interval. Figure B1 shows a typical recording of the GRF on force plate 1 for five transfer cycles. The weight of the subject was subtracted from the measured GRF and the difference was attributed to the dynamics of the nail gun created by the exertion of the user and the energy input from nail gun recoil.

Cumulative load was calculated for individual nail firing cycles as the integrated vertical load during the transfer phase. Multiple trials were conducted using two nail gun models and both SAT and CAT triggers. This cumulative load averaged 32.2 N over 0.87 s during the transfer phase. This reflects a 24% reduction in cumulative load relative to the act of statically supporting the weight of the nail gun for an equivalent duration (42.2 N× 0.87 s). Therefore, it was assumed that the effect of recoil energy in the transfer phase, *in flat nailing*, reduced cumulative load to 76% of the weight of the nail gun multiplied by transfer time.

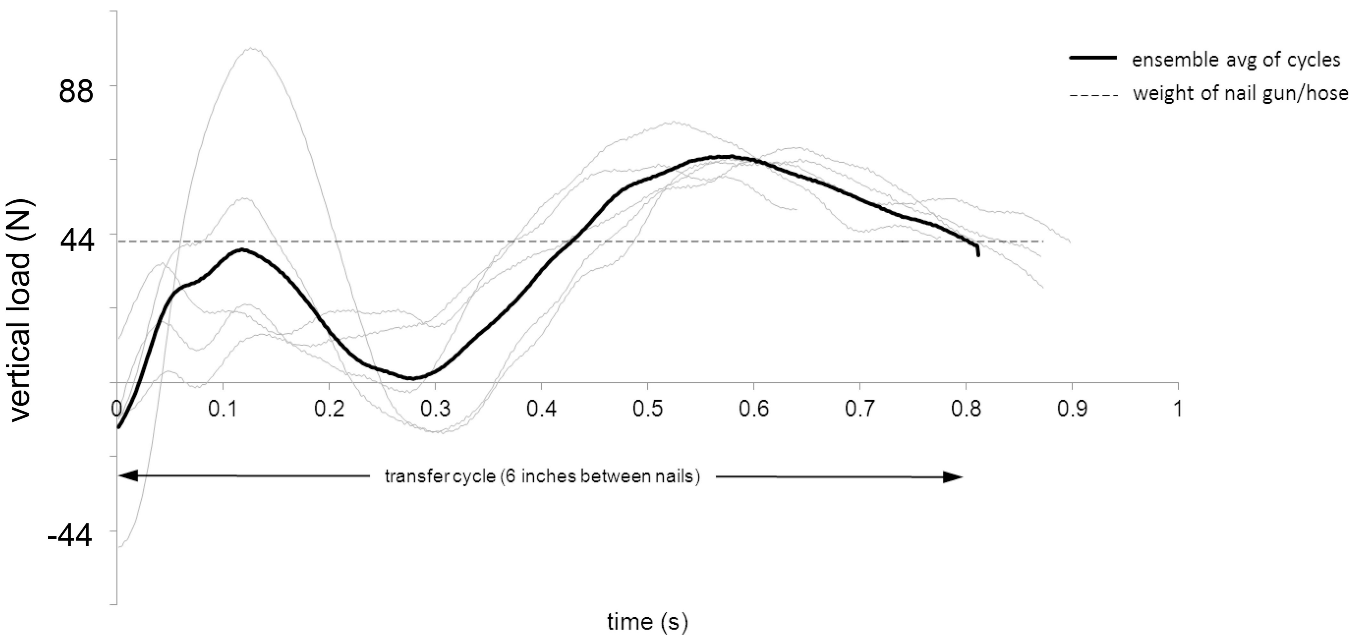

Figure B1.
Vertical load (defined as ground reaction force minus user's body weight) during the transfer phase. Five individual transfer cycles are shown (thin lines) with the time-normalized ensemble average (thick line). Cumulative load in the transfer cycle is the area under the ensemble average profile, which is 76% of the area under the horizontal dashed line (weight of the nail gun and hose).

APPENDIX C

Determination of Efficient Application of Tip Contact Force with the SAT

Efficient application of tip contact force is characterized by the temporal coordination of minimal press force to engage the nail gun safety tip against the workpiece followed by finger movement to activate the trigger. Tip contact force application was assumed to increase linearly to the target force level, and the minimum pressing force was assumed to provide a margin of safety of 25% above the spring resistance when the trigger is activated.

The duration of the linear increase in tip contact force and the duration of the target force level were derived from the MTM-1 element of *application of force* (Barnes, 1980). The MTM-1 *application of force* time allowance is accompanied by "*dwell time*" representing the latency preceding an intended reaction and release of force. In the case of nail gun use the applied tip force is released instantaneously by the firing recoil of the tool and there is no active release of force. The time allowances for *application of force* and minimum *dwell time* from MTM-1 were 122 ms and 151 ms, respectively. It was assumed that trigger activation occurs in parallel with the *dwell time* because the MTM-1 time allowance for a basic finger motion duration (72 ms) is well below the minimum dwell time.

From these assumptions tip contact force-time histories were constructed for theoretical efficient performance. Figure C1 illustrates a force-time history describing efficient tip contact force for a 37.7 N spring threshold. Testing of tip contact force dynamics with a force plate under the workpiece confirmed that a 273 ms tip contact duration is readily attainable with practiced use.

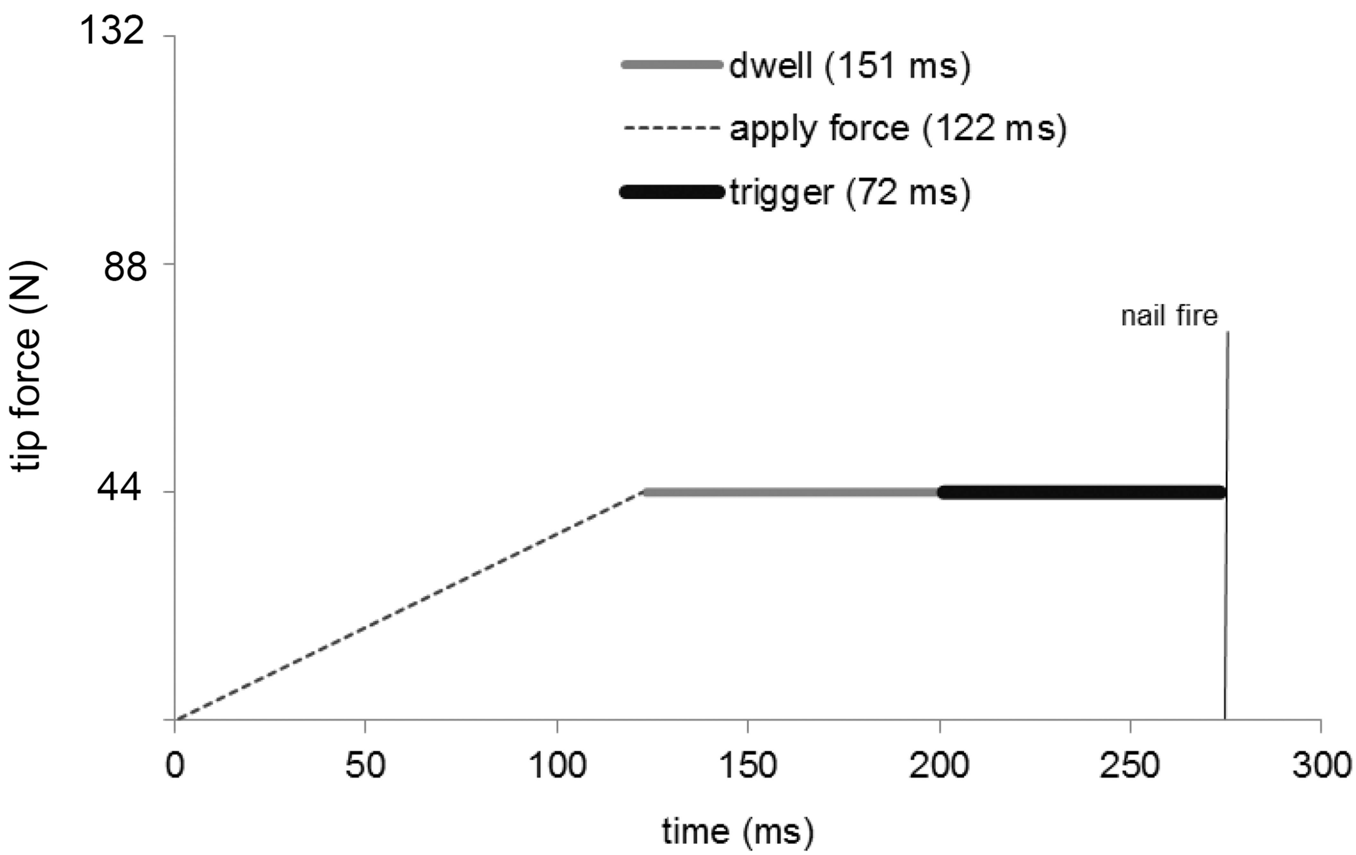

Figure C1.
Theoretical efficient performance with the SAT in the tip contact phase as derived from MTM-1 time/motion allowances assuming a 25% margin over the spring resistance. The total duration of tip contact is 273 ms.

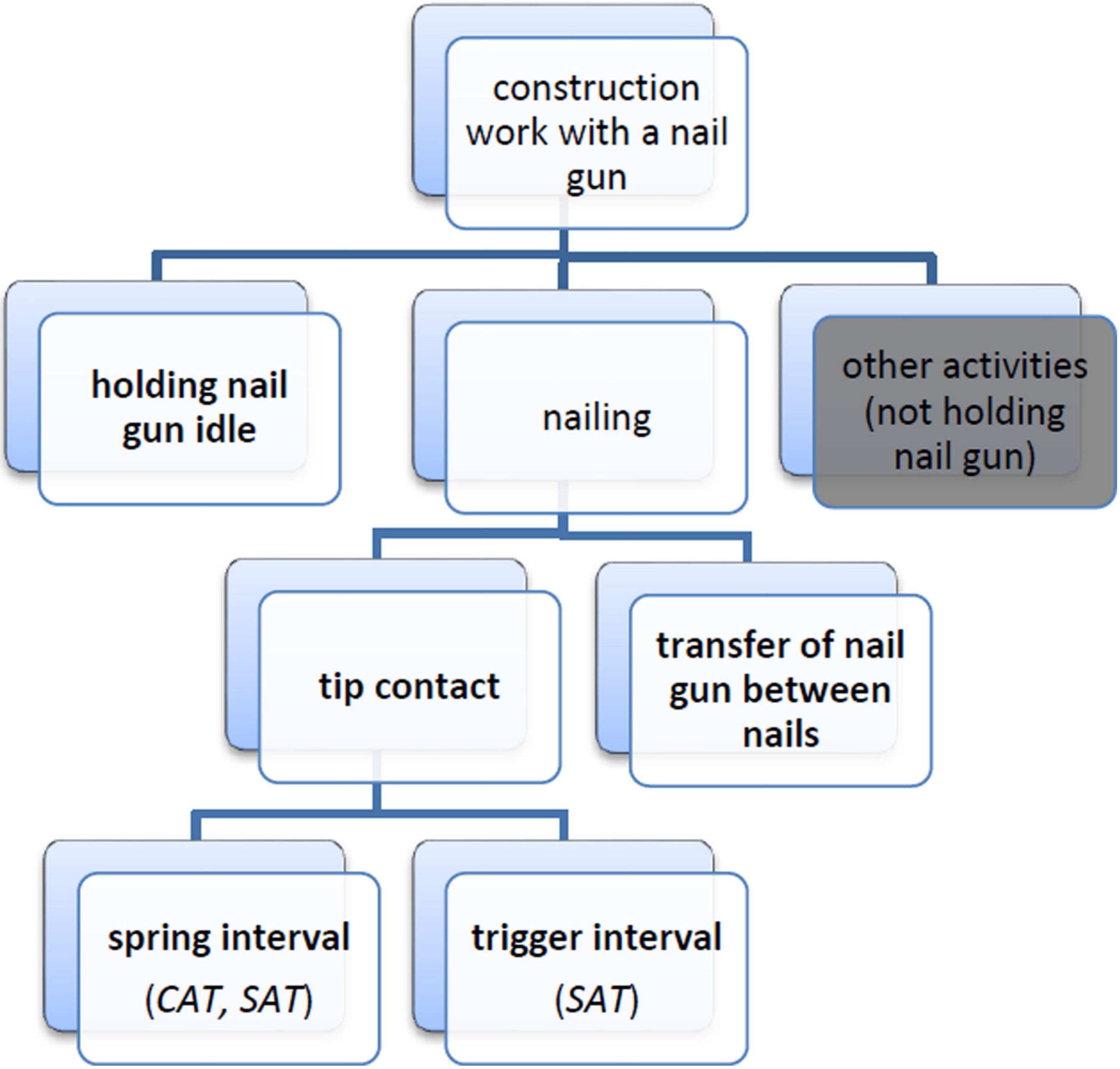

Figure 1.
Framework for evaluating hand force with PNG use. Activities for which the nail gun is not held in the hand are not considered.

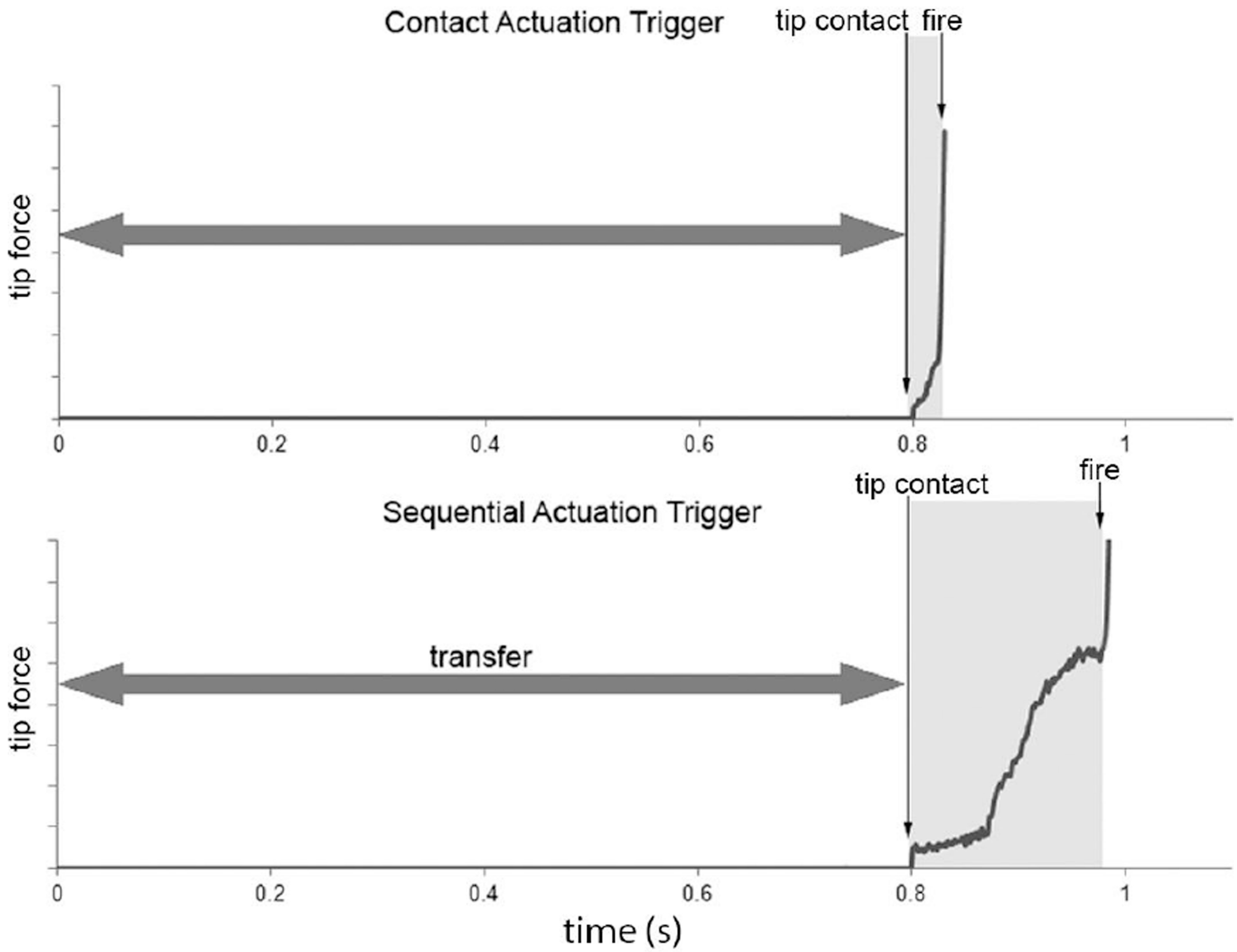

Figure 2.

Example of tip contact force measurement for a nail firing cycle for CAT and SAT trigger systems, with an average of 0.8 sec in the *transfer* of the nail gun between nails. The shaded regions represent the duration of *tip contact*. For the CAT, when the trigger is held depressed the duration of tip contact is equal to the spring interval, the period of time during which increasing tip force overcomes the spring threshold force at which point the nail is fired. For the SAT, the tip contact interval is comprised of a spring interval and a trigger interval and represents a longer time period of contact with the workpiece.

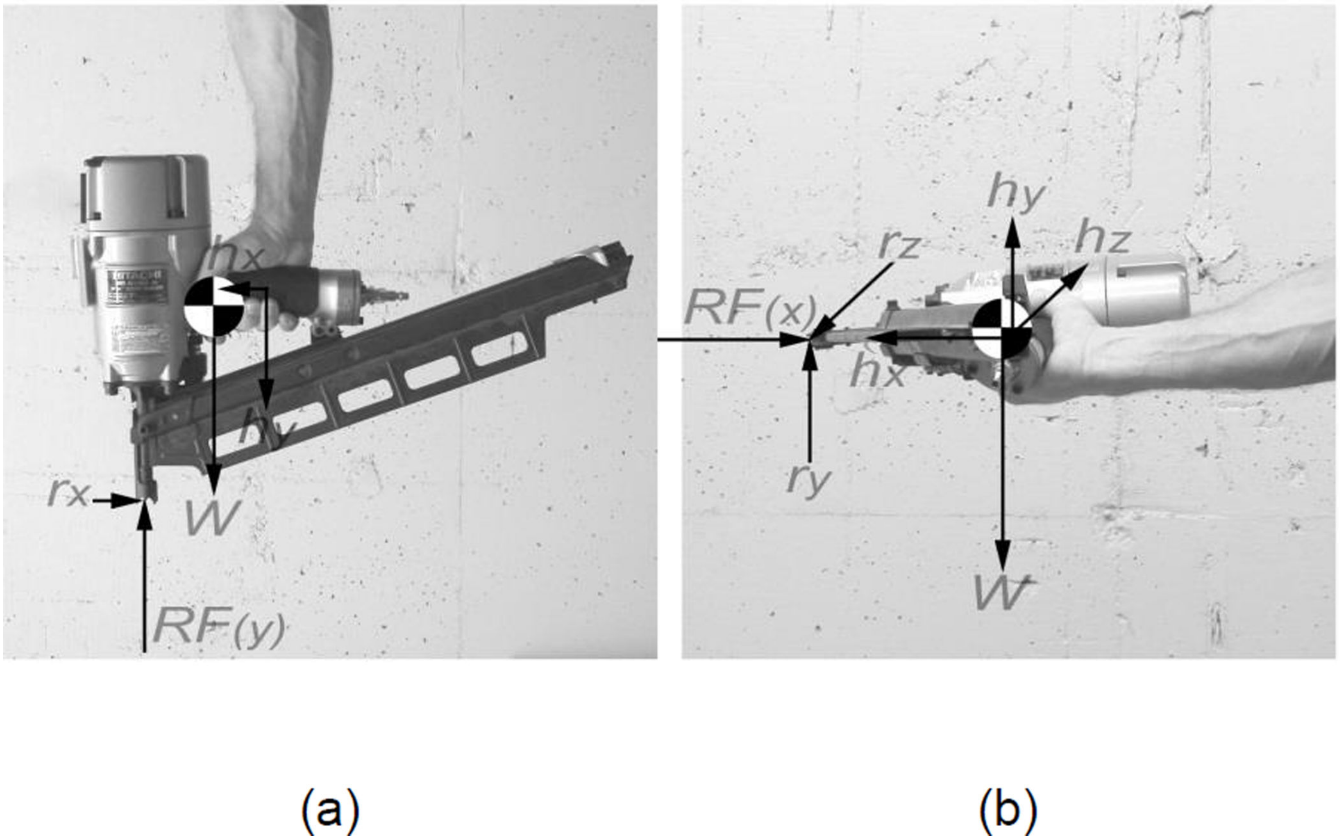

Figure 3.

Static forces acting on the nail gun in the tip contact phase in, (a) horizontal, and (b) vertical nailing orientations. In the horizontal orientation (a) $RF_{(y)}$ was measured on a horizontal force plate; in the vertical orientation $RF_{(x)}$ was measured on a vertically-mounted force plate.

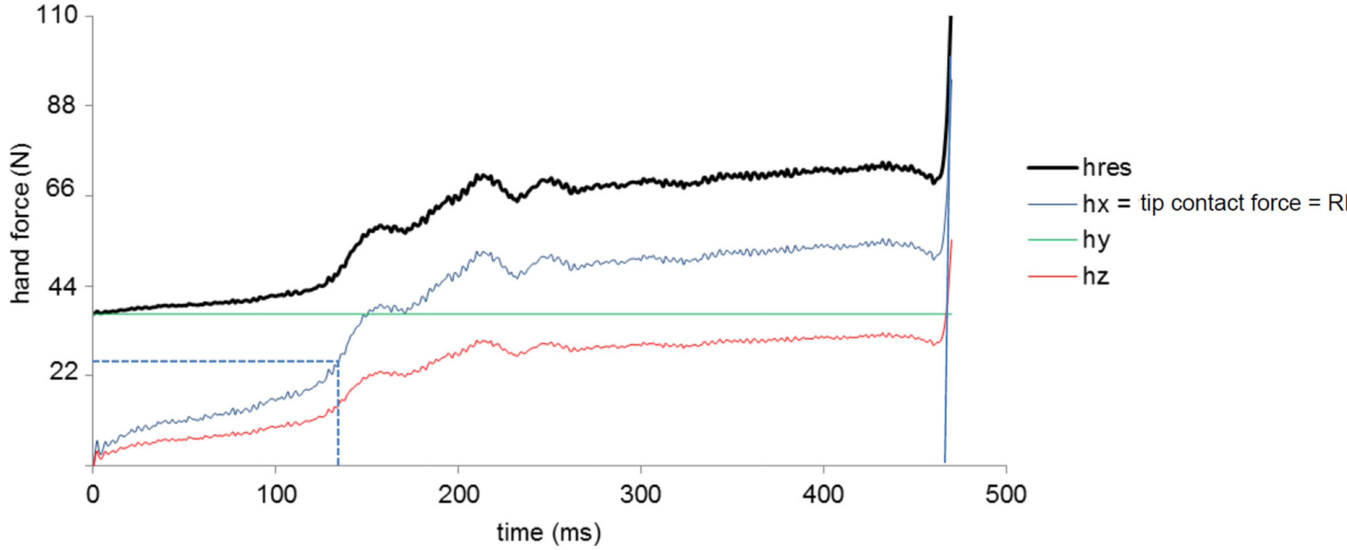

Figure 4.

Example of calculated resultant hand force (from measured h_x, and calculated h_y, h_z) in the tip contact interval for a vertical nailing trial with an SAT nail gun. The spring force threshold is 24.4 N. Thus, the spring interval is in the first 134 ms; the trigger interval is in the subsequent 335 ms. The cumulative hand force, calculated as the area under the h_{res} time history is 28.6 Nxs.

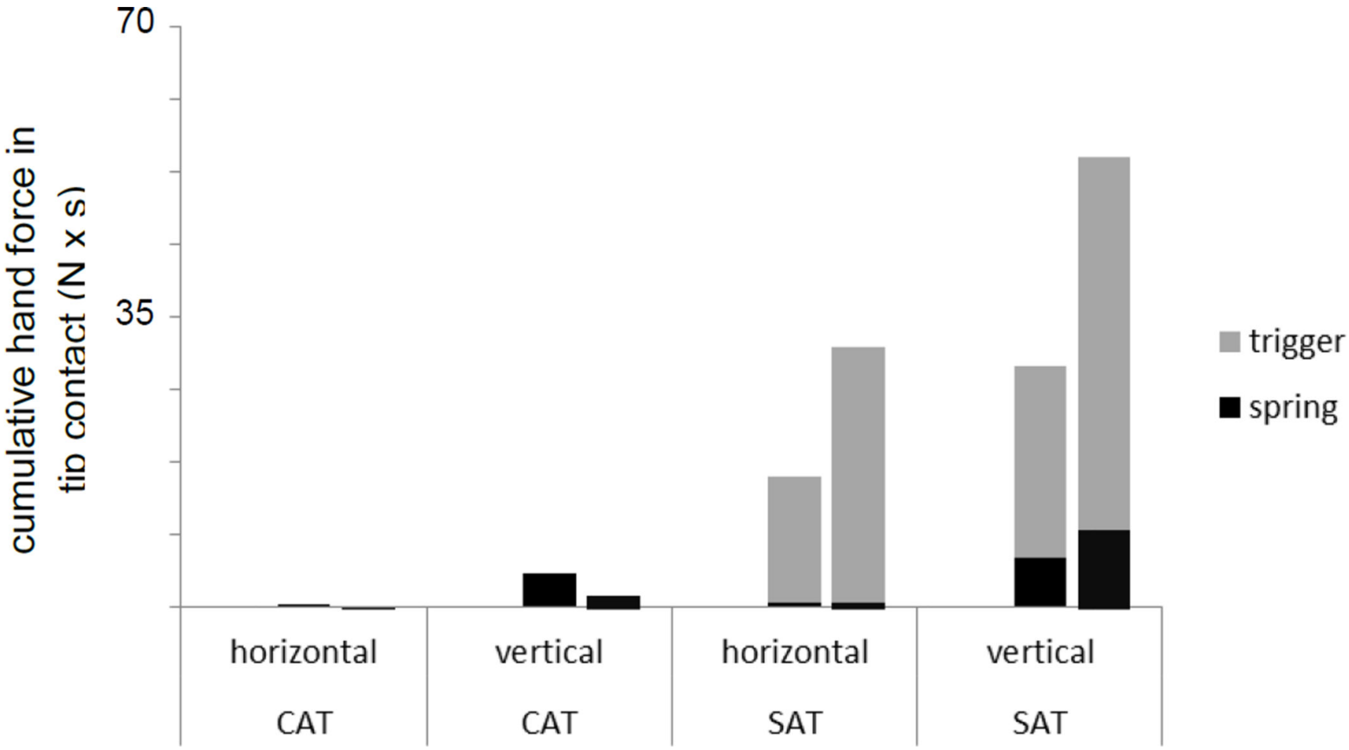

Figure 5.
Averages for cumulative hand force during tip contact interval as a function of nailing orientation and trigger. Data are from a single unpracticed nail gun user (see text). The pairs of bars represent the two nail guns tested.

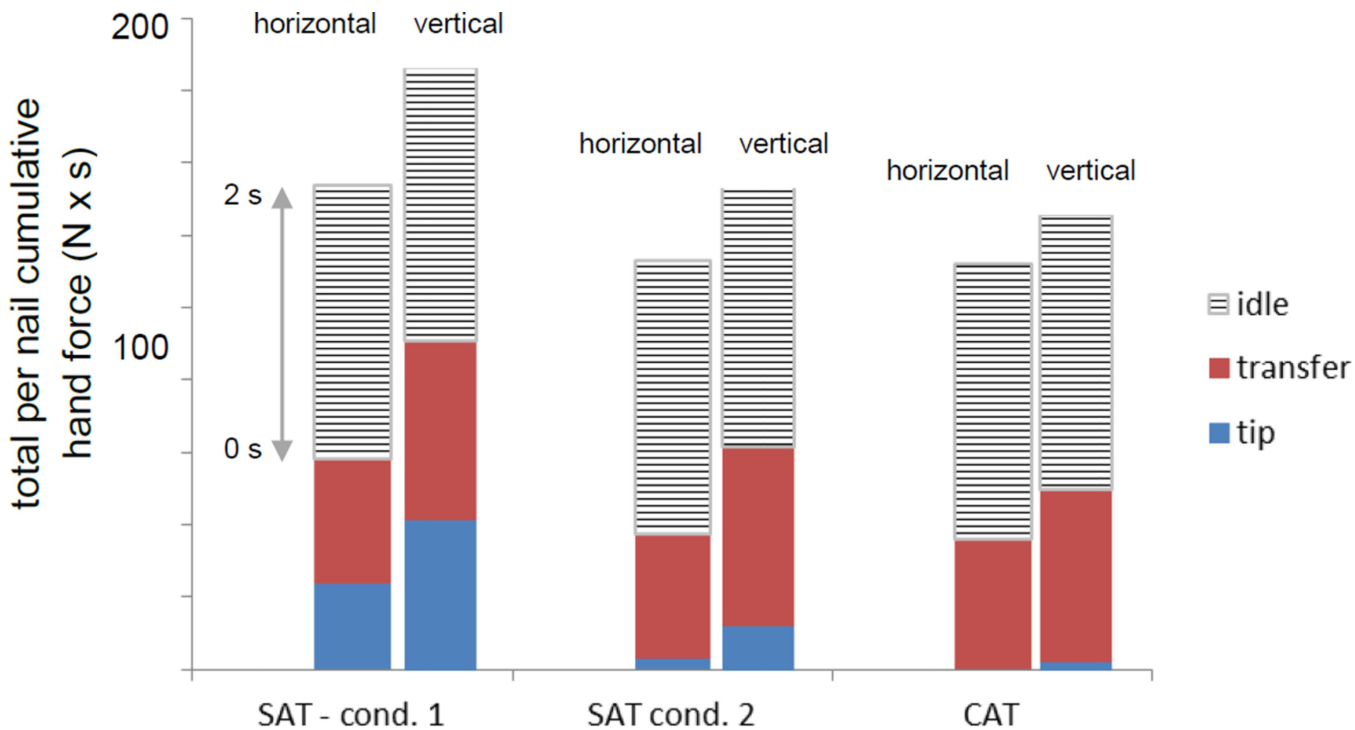

Figure 6.

Total hand force *per nail fired* as a function of trigger type/condition and task. (See text for descriptions of SAT - condition 1 and SAT - condition 2.) The total hand force is shown by the contribution of safety tip contact (blue), transfer (red), and various levels of idle hold time (hatched).