Smart Trigger
Development of a System to Improve Nail Gun Safety

By Mark L. Nagurka, Richard W. Marklin Jr. and Nathaniel R. Larson

Pneumatic nail drivers, commonly called nail guns, are used in construction and manufacturing, especially with high-volume fabrication and production (Figure 1, p. 32). They are powered by compressed air, operated by a finger trigger and are particularly useful for repetitive, intensive operations, such as nailing wooden studs, floor joists and plywood sheathing, and fastening roofing materials such as shingles to sheathing. In the past 20 years, pneumatic nail drivers, some of which can insert up to eight fasteners per second, have effectively replaced the hammer for driving fasteners on construction sites.

Pneumatic tools have two main types of trigger modes. With a contact-actuated trigger (CAT) tool, a worker can repetitively discharge fasteners by continuously pressing the trigger and bumping the tool's nosepiece against the work surface. With a sequential-actuated trigger (SAT) tool, the worker presses the tool's nosepiece against the work surface and then presses the trigger to discharge a fastener. A SAT tool requires the worker to remove contact with the nosepiece and release the trigger before another fastener can be discharged. Wood frame building workers and residential roofers typically use CAT tools because they have higher production rates than SAT tools (i.e., more fasteners are installed per unit time).

Pneumatic nail drivers can drive fasteners into unintended surfaces, such as a user's hands, arms and clothing. Acute injuries can occur from accidental discharge of fasteners. Past studies have investigated the incidence and severity of acute injuries associated with pneumatic tools among construction workers in several states and among nonoccupational and occupational operators who were treated for acute injuries in emergency rooms of major U.S. hospitals. The relative rate of acute injury from accidental fastener discharge was twice as high for CAT tools as for SAT tools (Lipscomb, Dement, Nolan, et al., 2006; Lipscomb, Nolan, Patterson, et al., 2008a; 2010a; 2010b; U.S. CPSC, 2002a; 2002b).

A smart trigger system for a pneumatic nail gun can reduce the risk of an acute injury to the user or bystander. An acute injury is an accidental discharge of a fastener (typically a nail or staple) that impales or otherwise injures the user or bystander; the most common sites of injury are the hands, arms and legs. The smart trigger system uses an optical light sensor to determine whether the material surface is an intended substrate for fastening. The system can be integrated into tools with various power sources and common trigger systems.

A chief advantage of the smart trigger system is that it allows the user to maintain the fast production rate of the CAT, while reducing the risk of acute injury from accidental fastener discharge. The smart trigger system can be integrated into the housing of a commercial fastening tool, regardless of the power source (e.g., pneumatic, hydraulic, electric, gas discharge).

To reduce the risk of accidental discharge of a fastener without compromising the production rate of the CAT tool, the authors designed and built a prototype smart trigger system for a powered fastening tool that can be used with either a CAT or SAT system. The smart trigger system uses an optical light sensor to determine whether the material surface is an intended material for fastening. If the material surface matches an image of the intended material (from calibration), the system allows the tool to insert a fastener. If there is no match, the system prevents fastener discharge.

IN BRIEF
- Accidental discharge of a fastener from a pneumatic nail gun can result in acute injury to construction workers or consumers. Such injuries most commonly impale the hands, arms and legs.
- A smart trigger system can reduce the risk of acute injuries by detecting whether the surface is an intended substrate for fastening.
- This article details the development of a smart trigger system, including testing methodology and results.

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FIGURE 1
Typical Pneumatic Framing Nail Driver & Coiled Roofing Nail Driver
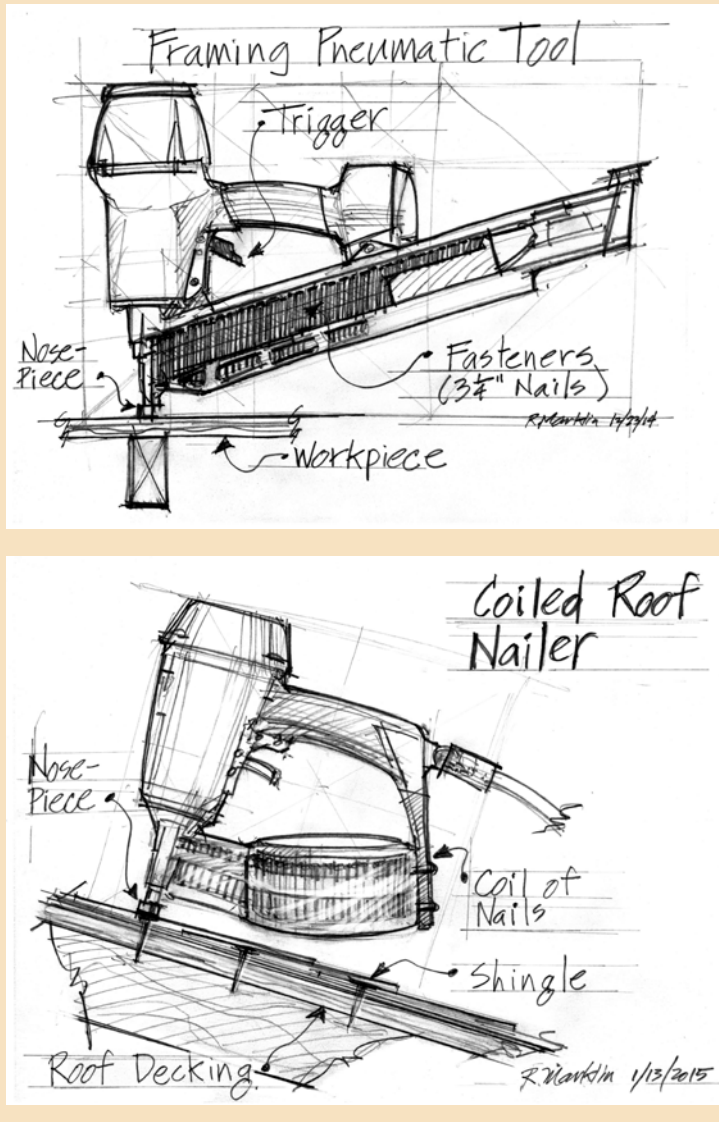
The developers integrated the smart trigger system into a commercial Bostitch wood-framing nail driver (model F21PL, N88RH-2MCN, 1.5 to 3.5 in. fasteners). The system can reduce the risk of acute injury to users or bystanders due to accidental discharge of a fastener. The developers filed a patent application for the smart trigger system on April 15, 2016 (PCT/US16/27867).

The authors conducted a limited field test of the trigger system, which produced positive results. A more rigorous study of varied construction materials and skin colors and tones of users is required before commercial deployment. The authors tested a prototype of the system under limited conditions with a small sample of 150 observations. More rigorous and expanded testing of the trigger system with greater variety of construction materials, clothing and user skin color is required before commercial use. The system is in the early stage of development; the authors are pursuing a manufacturer partnership to deploy the system with an array of powered fastening tools.

This article describes the trigger system in detail after presenting a review of the literature of acute injuries from pneumatic nail guns.

Literature Review

The epidemiological literature of injuries from pneumatic nail drivers has relied principally on data from construction workers in North Carolina (Dement, 1999; Dement, Lipscomb, Li, et al., 2003) and Washington state (Baggs, Cohen, Kalat, et al., 2001), union carpenters (Dement, et al., 2003; Lipscomb, Dement & Behlman, 2003; Lipscomb, Dement, Li, et al., 2010; Lipscomb, Dement, Nolan, et al., 2003; 2006; Lipscomb, Nolan, Patterson, et al., 2008b; 2010a; 2010b), and reports of injuries to consumers and workers treated in emergency rooms of major U.S. hospitals (Lipscomb, Schoenfisch & Shishlov, 2010; Lipscomb, Schoenfisch, Shishlov, et al., 2010; Schoenfisch, Lipscomb, Shishlov, et al., 2010; U.S. CDC, 2007; U.S. CPSC, 2002a; 2002b).

These studies are descriptive (i.e., case reports and cross-sectional) or observational (i.e., cohort studies) and used large sample sizes to calculate the incidence rates of acute injuries based on exposure time and relative ratios of various workplace factors. Some studies were conducted prior to the ANSI (2002) standard that mandated that pneumatic drivers (excluding light-duty tools, heavy-duty staplers and coil nailers) be offered with SAT capability. The percentage of tools with CAT versus SAT mechanisms used in the workplace when the studies were conducted may not be representative of current usage.

Injury Scenarios & Body Parts Affected

Two prominent injury scenarios associated with pneumatic nail drivers were reported in major studies conducted by U.S. Consumer Product Safety Commission (U.S. CPSC, 2002a; 2002b) and by U.S. CDC (2007). These data were collected by the National Electronic Injury Surveillance System (NEISS), which records incident reports of cases treated at emergency departments of major U.S. hospitals. During the 5-year period from 1996 to 2000, NEISS estimates 53,153 injuries from pneumatic nail guns occurred in the U.S., with 34,724 to the hand/finger. Of hand/finger injuries, 85% (29,225) were due to puncture/foreign bodies. During this 5-year period, the injuries increased at a rate of approximately 1,200 per year (U.S. CPSC, 2002b).

During the period from Aug. 1, 2000, to July 15, 2001, NEISS recorded the number of injuries related to pneumatic nail guns that were treated at major U.S. hospital emergency rooms (U.S. CPSC, 2002a). A total of 15,929 injuries were work-related, while 9,562 were not work-related, resulting in 25,491 total injuries during the nearly 1-year period.

The two major injury scenarios were accidental firing of the tool and accidental contact with a surface. These two scenarios accounted for 47% (7,476 of 15,929) of occupational injuries and 62% (5,987 of 9,562) of nonoccupational injuries. The two most common causes of injuries not due to accidental firing or contact were nail hit knot in

wood (3,872, 15% of total) and nail went through wood (3,580, 14% of total). In a follow-up study from 2001 to 2005 (U.S. CDC, 2007), the annual work-related nail gun injuries treated in emergency rooms ranged from 19,300 to 28,600, with an average of 22,200. The annual number of injuries to consumers (not work-related) ranged from 13,400 to 16,200, with an average of 14,800 injuries.

Typical scenarios of accidental firing occur when the user's finger is on the trigger under the following conditions:

•Nosepiece of the tool touched a knot or imperfection in the wood, causing the tool to discharge twice.

•Tool kicked back and discharged a second fastener.

•User tripped on the air hose and tool discharged a fastener.

•User dropped the tool and it discharged a fastener.

•User picked up the tool by the air hose, causing the tool to discharge a fastener (U.S. CPSC, 2002a).

Typical scenarios of accidental contact occur when the user's finger is on the trigger under the following conditions:

•User tripped over air hose and body part contacted the tool's nosepiece.

•User was climbing on ladder when the body part contacted the tool.

•User was reaching for material and brushed body part across tool.

•User was walking down roof and tool made contact with body part.

•User was working on a roof and tool made contact with body part (U.S. CPSC, 2002a).

Hand/fingers were the most common site of injury, occurring in 67% of all nail gun injuries reported by Washington state from 1990 to 1998 (Baggs, et al., 2001). Puncture wounds were the most common nail driver injuries to the hand/fingers. In a study of carpenters in Ohio from 1994 to 1997 and in North Carolina from 1996 to 1999, Dement, et al. (2003), found that 80% to 89% of all injuries to the hand/fingers were puncture wounds. CPSC (2002b) found similar results, with 84% of the total hand/finger injuries resulting in punctures. Of accidental firing injuries in the CPSC (2002a) study, 78% of all injuries were to the upper arm, wrist, hand or fingers of workers, and 95% were to the same body parts of consumers. Of accidental contact injuries, the most frequently injured body parts were the thigh, knee, lower leg or foot (percentages not reported).

Acute Injury Incidence Rates

Studies of the frequency of pneumatic nail gun injuries were conducted in three U.S. states (i.e., North Carolina, Ohio, Washington). These studies reviewed claims recorded by state workers' compensation systems from workers who were injured using nail guns. The geographic diversity of the sites and data sources (workers' compensation systems) provides a representative cross section of pneumatic tool injuries to U.S. workers. Following are details about the methodology of the studies at the three sites:

•North Carolina: All workers' compensation claims from 1986 to 1994 among 7,400 North

FIGURE 2
Prototype Smart Trigger System

Schematic (top) and photograph (bottom) of the prototype smart trigger system incorporated into a Bostitch pneumatic framing tool. This tool drives nails up to 3.5-in. long. All the hardware (components and cabling) of the system would be integrated into the housing of a commercial tool to prevent damage to components and to make it the same form factor of a typical tool.
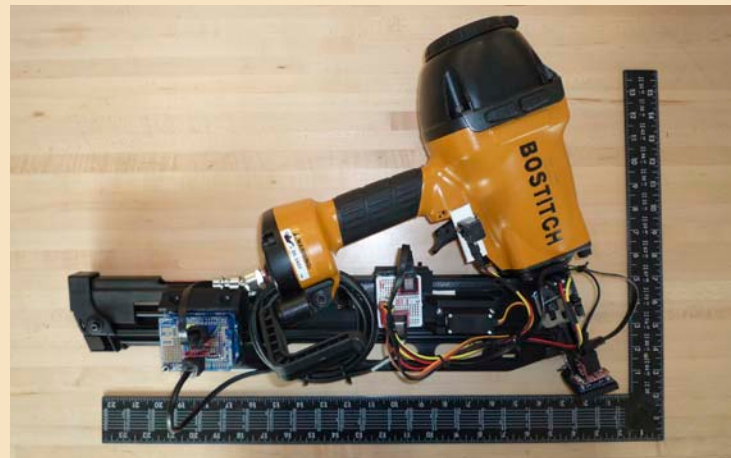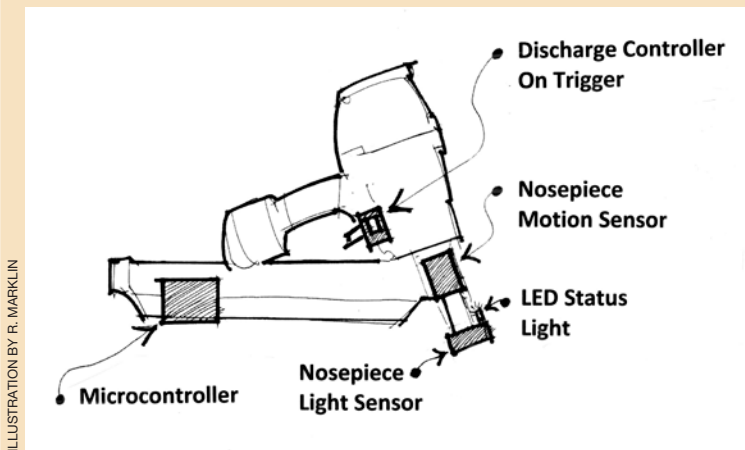
Carolina Homebuilders Association members and their subcontractors were reviewed to identify the incidence rate of nail gun injuries (Dement, 1999). Claims from the same builders' association from 1995 to 1999 resulted in 377 nail gun injury claims (Dement, et al., 2003).

•Ohio: 139 nail gun injury claims from 1995 to 1997 from 13,487 construction workers were recorded by the Ohio Bureau of Workers' Compensation (Dement, et al., 2003).

•Washington: 3,613 nail gun injury claims from 1990 to 1998 were recorded by the Washington State Workers' Compensation database (Baggs, et al., 2001).

Following is a summary of incidence rates (IR), normalized to 200,000 hours of exposure, or frequencies of nail gun injuries from these three studies:
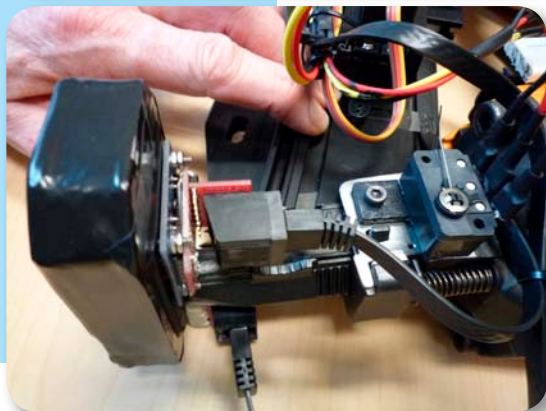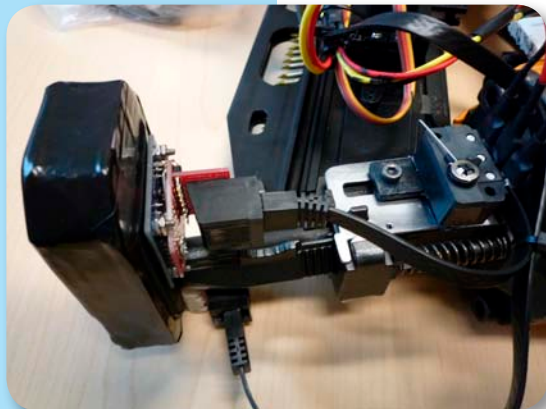
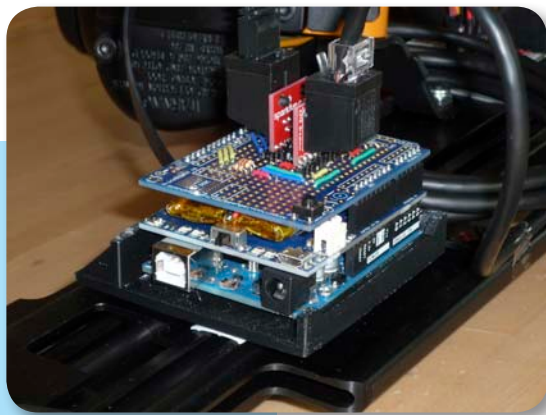•73% of all nail gun injuries in Washington state occurred in the construction industry (Baggs, et al., 2001).

•In the North Carolina study, the highest lost-time medical cost IR for a mechanism of injury was struck by (IR = 3.1), which Dement (1999) interpreted as including nail gun injuries.

•The nail gun injury IR was 0.33 and 0.26 in North Carolina and Ohio, respectively (Dement, et

Photo 1 (top): An Arduino microcontroller with a rechargeable lithium battery compares the values of the RGBW light levels from the light sensor to a set of RGBW light levels of the target substrate. Based on the difference, a decision is made whether the target is the intended target. If it is, fastening can proceed.

Photos 2 (center) and 3 (bottom): Nosepiece motion sensor. Pressing the nosepiece against a substrate pushes the nosepiece mechanical linkage against a servomotor switch. Photo 2 shows the nosepiece in its idle state (not pressed against a substrate); Photo 3 shows the nosepiece pushed against a hand (substrate), which moves the wire needle on the servomotor switch.

approximately constant (1.9 to 2.0). Other studies (Lipscomb, Dement, Nolan, et al., 2006; Lipscomb, Nolan, Patterson, et al., 2010a) found a similar RR (2) of injuries associated with CAT to SAT tools.

Smart Trigger System

The smart trigger system (Figure 2, p. 33) incorporates a microcontroller and optical light sensor that records the red, green, blue and white (RGBW) light levels reflected from the intended material surface, called the target substrate. The system uses the measured RGBW light levels of the target substrate to determine whether the tool drives or does not drive a fastener into a substrate. When the tool's nosepiece is pressed against a substrate, the smart trigger system measures the reflected RGBW light levels and compares them to those of the target substrate. If the light levels of the substrate match (within a small tolerance) the RGBW light levels of the target substrate, then the trigger system's controls logic allows the tool to insert a fastener. If the light levels of the substrate do not match the levels of the target substrate, then the trigger system's controls logic does not allow the tool to discharge a fastener.

The smart trigger system has the following novel elements:
- microcontroller (Photo 1);
- LED status light (Figure 2);
- nosepiece motion sensor (Photos 2 and 3);
- nosepiece light sensor (Photos 4 and 5);
- discharge controller on trigger (Photo 6).

To start the smart trigger system, the user presses a button switch on a microcontroller (Photo 1), which is located at the rear of the tool (Figure 2). Pressing this switch initiates the smart trigger system for the tool to measure the light levels of a target substrate, such as a shingle, two-by-four or plywood. The LED status light (Figure 2) turns red, indicating that the tool is ready for calibration to a target substrate. The user presses the tool's nosepiece against the target substrate; the nosepiece motion sensor (Photos 2 and 3) in the smart trigger system senses when the nosepiece is pressed against a substrate. Pressing the nosepiece against a substrate pushes the nosepiece mechanical linkage against a servomotor switch that sends a signal to the microcontroller, which commands the nosepiece light sensor (Photos 4 and 5) to measure the RGBW light levels of the target substrate.

Four LEDs mounted around the light sensor illuminate the surface of the substrate for the light sensor to measure the RGBW light levels under constant conditions, regardless of ambient light levels. A black enclosure surrounds the LEDs and light sensor to minimize ambient light illuminating the target surface.

The nosepiece light sensor measures each of the four levels (RGBW) of the target substrate, on a scale from 0 to 255. It then sends these four values to the microcontroller (Photo 1). These are stored as the light levels of the calibrated target substrate. After a target substrate has been calibrated, the LED status light turns green, indicating that the user can now use the tool to insert fasteners.

al., 2003). Nail driver injuries accounted for 8.3% to 25.5% of all lost-time claims of construction workers in the North Carolina and Ohio studies.

- The average nail driver IR was 0.03 for all construction workers in Washington state (Baggs, et al., 2001). IR was highest (IR = 2.06) for workers in the wood frame building construction and second highest (IR = 0.66) for interior finish carpentry. The nail gun IRs for these two sectors increased per year on average 6.5% and 4.1%, respectively, from 1990 to 1998.

Effect of Trigger Actuation System

Nail guns with the CAT system were indicated in more emergency department hospital cases than SAT tools (U.S. CPSC, 2002a; 2002b). Approximately 69% of nail gun injuries were associated with CAT tools and 31% with SAT tools. This approximate 2:1 relationship was corroborated by Lipscomb, et al. (Lipscomb, Dement, Nolan, et al., 2003; Lipscomb, Nolan, Patterson, et al., 2010b), who found that the relative ratio (RR) of injuries to users with CAT tools compared to SAT tools was

Side (Photo 4, left) and bottom (Photo 5, right) views of the nosepiece light sensor. Four LEDs illuminate the substrate for the light sensor to measure its RGBW light levels. A black enclosure (Photo 5) surrounds LEDs and sensor to protect them and minimize effects of ambient light.

Photo 6 (bottom): Discharge controller on trigger actuates fastener discharge when trigger is pulled. The servomotor is connected to the trigger by a thin metal rod (through a hole in the trigger). When activated, the servomotor pushes the rod against a button inside the trigger that allows the piston cylinder to discharge a fastener.

After calibration, a user intending to discharge a fastener into a target substrate presses the tool's nosepiece against the material. RGBW light levels of the material are then sent to the microcontroller and compared to the set of RGBW levels of the calibrated target substrate. The analysis protocol in the microcontroller determines whether there is a match between the new set of RGBW light levels and the set of light levels from the target substrate.

If there is a match (within a small percentage of each RGBW light level), the microprocessor is programmed to allow the tool to insert a fastener into the substrate by sending a signal to the discharge controller on the trigger (Photo 6). With a signal from the microcontroller, the servomotor pushes a thin rod (which passes through a hole in the side of the trigger) against a button inside the trigger, which allows the piston cylinder to discharge a fastener.

As a fastener is discharged, the LED status light turns blue. If the new RGBW levels from a substrate do not match the RGBW levels of the calibrated target substrate, then the microprocessor does not allow the tool to insert a fastener, even if the user were to pull the trigger repeatedly. This protocol has the potential to reduce the probability of the tool discharging a fastener into an unintended surface (nontarget substrate), such as a hand, arm or clothing.

Testing Methodology
Accuracy, Sensitivity & Specificity

A limited field test of the prototype smart trigger system (Figure 2) was conducted indoors and outdoors to determine its technical feasibility and to compute the system's accuracy, sensitivity and specificity. The field test was limited to one construction material, one piece of clothing (jeans) and one user/skin color, thus the results of this limited test are insufficient for commercial deployment of the system at this time. More thorough field testing is required.

Accuracy is defined as the tool's ability to correctly identify whether a material is a calibrated target substrate or a nontarget substrate. If the target substrate is identified correctly, then the tool inserts a fastener into the target substrate. If a nontarget substrate is identified correctly, then the tool does not insert a fastener. Examples of nontarget substrates are skin, pants, shirts and nontarget construction materials. Insertion of a fastener into a nontarget substrate can cause an acute injury to the user or bystander.

Following are the four possible decisions of the smart trigger system:

•True positive: a substrate identified correctly as the calibrated target substrate.

•False positive: a nontarget substrate identified incorrectly as the target substrate. A false positive occurs when the tool inserts a fastener into a material that is not the calibrated target substrate. False positives are significant because they can cause an acute injury, the result of the tool inserting a fastener into a body part.

•True negative: a substrate identified correctly as a nontarget substrate.

•False negative: a target substrate identified incorrectly as nontarget substrate. A false negative is a miss, which means the tool did not insert a fastener into the calibrated target substrate. False negatives are significant because they can lead to a user's frustration with the tool (not being able to insert fasteners into the intended material) and may lead to a user making unauthorized changes to a tool to override the trigger system.

Calculation of false positives and false negatives is a conventional method of measuring the sensitivity and specificity of a tool. *Sensitivity* is a measure of the true positive rate, or the proportion of times that the calibrated target substrate is identified correctly

Photos 7 and 8 (left to right): Station for testing technical feasibility of prototype smart trigger system. A tan-colored asphalt shingle (Photo 7) was mounted to plywood on a 4 x 8-ft wooden structure (Photo 8) with a 4/12 pitch (18°), built to resemble a slanted roof. Illumination level was measured with a light meter (Photo 7).

by the tool and the tool inserts a fastener into the target substrate. *Specificity* is the true negative rate, or the proportion of times that a material other than the target substrate is identified and the tool does not insert a fastener into the nontarget substrate.

Test Fixture & Target Substrate

Almost all roofers use pneumatic nail drivers to install roofing shingles; for this reason, an asphalt shingle was chosen as the calibrated target substrate. A tan colored shingle (a common color of roof shingles), was mounted on a 4 x 8-ft plywood test fixture with a slope of 18° (4/12 pitch) (Photos 7 and 8). The test fixture is portable so it can be moved into various lighting conditions.

The prototype tool was tested in two lighting conditions, indoors with overhead LED lights (473 lux) and outdoors on a partly cloudy day (15,691 lux) in December 2015. [Lux is the SI measure of illumination; 1 foot-candle (U.S. customary unit) of illumination is equivalent to 10.87 lux.] The illumination levels in lux were measured with a light meter shown in Photos 7 and 8.

The tool user was a right-handed 22-year-old White male with light-colored skin. He was an undergraduate engineering student from Minnesota who had experience using pneumatic nail drivers on construction sites.

Target & Nontarget Substrates

The target substrate for the tool was the tan shingle shown in Photos 7 and 8. Four other materials, called nontarget substrates, were included in the test to determine whether the tool had sufficient specificity to identify them:
•denim material on the user's thigh (medium blue color);
•palm of user's left hand;
•back (dorsal side) of user's left hand;
•conventional wood two-by-four (untreated).

Prototype Tool & Analysis Protocol

The smart trigger system attached to the Bostitch tool (Figure 2) was fully functional during the field test. The air piston and pneumatic hose of the tool were disabled so that the tool could not discharge a fastener. This expedited the experiment and eliminated the possibility of an accidental discharge of a fastener.

The controls threshold of the smart trigger system was set to ± 1.5% of the RGBW light settings to de-

tect the calibrated target substrate. In other words, if the light sensor measured a light level (0 to 255 levels) within ± 1.5% of the light level for each color (R, G, B or W) of the target substrate (i.e., the tan shingle in the experiment), then the measured substrate was deemed to be a target substrate. If any of the R, G, B or W light levels was outside ± 1.5% of the target substrate light levels, then the measured substrate was deemed to be a nontarget substrate and the tool did not discharge a fastener.

Experimental Protocol

The test was conducted on Dec. 11, 2015, at 11:40 a.m. in Milwaukee, WI, indoors in the ergonomics laboratory and outdoors facing south so that sunlight was not obstructed by any object. There were 75 trials in each lighting condition, with each of the five material test conditions [i.e., calibrated tan-colored shingle (target substrate) and the four nontarget substrates] repeated 15 times. The presentation order of the 75 trials was counterbalanced to eliminate carryover and learning effects.

The experiment started with the tool user calibrating the tool to the tan-colored shingle. After the LED status light (Photos 2 and 3) displayed a green color, the user then pressed the nosepiece of the prototype tool against the first of the five substrates in the sequence of 75 trials. An observer recorded the material condition and whether there was a blue light on the LED status light (Photos 2 and 3). A blue light indicated whether the fastener would have been discharged into the substrate (i.e., activation of the discharge controller, Photos 7 and 8). Then the user proceeded to the next substrate until all 75 trials were completed.

Test Results

•Indoors: Of the 75 trials, no false positives and two false negatives occurred. Thus, the sensitivity was 86.7% (13 true positives/15 positive conditions) and the specificity was 100% (60 true negatives/60 negative conditions). The accuracy was 97.3% (73/75).

•Outdoors: No false positives and no false negatives occurred, resulting in sensitivity and specificity of 100%. The accuracy was 100% (75/75).

Discussion

Accuracy of at least 97.3% from the field study demonstrates the feasibility of the smart trigger

system in two tested lighting conditions, with the tan shingle as the target substrate and the light-colored skin of the tool user. The only errors were two false negatives in the indoor condition, which means that the smart trigger system was protective of the tool user. With false negative errors, the trigger system did not allow the tool to discharge a fastener even though the tool's nosepiece was pressed against the target substrate. A more serious error, which did not occur, would have been false positives, in which case the tool would have discharged a fastener into the user's arm or leg, either directly or through clothing.

The smart trigger system allows a worker to calibrate the tool to a target substrate, then discharge fasteners on only that substrate at a rate as fast as a conventional CAT pneumatic nail gun. The capability of the smart trigger system to work with a CAT tool is essential, as a large percentage of construction workers demand a tool with a high rate of fastener insertion, based on a small sample survey of pneumatic tool users conducted by the authors.

The study of 15 male pneumatic nail driver users in the upper Midwest was conducted to gain insight into how pneumatic tools are used on construction sites and in manufacturing plants. The survey represented a cross section of pneumatic tool users in the Midwestern U.S. Four of the 15 users are or had been union workers, and two of the workers were Latino. The following workers were interviewed:

- three remodelers who perform rough and finish residential carpentry;
- two commercial carpenters (wood and steel studs);
- three wood framers who build residential houses and commercial buildings;
- two pallet assemblers (manufacturing);
- five roofers (three commercial, two residential steep slope).

The main survey results are summarized here:

- 12 of the 15 workers use CAT tools on their job; the three union commercial roofers use only SAT tools.
- Among the 15 workers, 12 acute injuries occurred during their careers due to pneumatic tool use, six workers with one injury each and three workers with two injuries each.
- 13 of the 15 workers said the CAT system was effective, and 8 of the 15 said the SAT was effective.
- No workers modified their pneumatic tools without authorization; two workers changed the trigger mechanism to CAT using the manufacturers' authorized parts and methods.
- 14 of the 15 workers said there should be no restrictions on the distribution of CAT pneumatic tools. One worker said there should be some restrictions; he said only workers who have certification should use CAT tools. The three union commercial roofers said there should be no restrictions on the distribution of CAT tools, although these workers use only SAT tools. Reasons cited for not wanting restrictions include: "You can manage the risk" (remodeler); "carpenter should have choice" (two remodelers); "safety depends on individual" (two of the three union roofers); and "SAT tool is too slow" (four workers).

The smart trigger system for powered fastening tools has the potential to reduce the number of acute injuries to construction workers and consumers from accidental fastener discharge, particularly with CAT tools, as these tools have been shown to have twice the risk of acute injury than SAT tools (Lipscomb, Dement, Nolan, et al., 2003; 2006; Lipscomb, Nolan, Patterson, et al., 2010a; 2010b;). NIOSH reports that from 2001 to 2005 approximately 22,000 workers and 14,800 consumers annually suffered pneumatic nail gun injuries that were severe enough to warrant emergency-room treatment (Lowe, Hudock, Earnest, et al., 2015). Thus, almost 37,000 acute injuries per year were due to pneumatic nail drivers' accidental firing or contact.

The medical cost of acute injuries from accidental discharge of fasteners would likely decrease with the smart trigger system, thereby reducing the cost to employers, workers' compensation systems and private healthcare systems. According to a study of 954 injury claims from union carpenters in the St. Louis, MO, region from 1995 to 2000, the average cost of a struck by/against injury, which likely included nail driver injuries, was $3,855, the third most costly on average (Lipscomb, Dement & Behlman, 2003). Based on statistics from Federal Reserve Bank of St. Louis (2017), medical care cost has risen by an average of 3.64% per year for U.S. urban consumers since 2000, which resulted in an increase of 77% over the period from 2000 to 2016.

Thus, the average cost of a struck by/against injury is likely to be $6,833 in 2016. Assuming a conservative estimate of 22,000 workers annually suffering an acute injury from accidental discharge and an average medical cost of $6,833 per case, the total medical cost of acute injuries from pneumatic nail guns is more than $150 million per year for workers. If injuries to consumers were included, the total cost would be much greater. If the smart trigger system were to decrease the number of acute injuries by 25%, the cost savings of medical expenses would be at least $37 million per year.

Limitations of Field Test

The conditions of the smart trigger system field test were limited and it would not be appropriate to generalize the test results to the population of all pneumatic tool users under all conditions. Following are limitations with recommendations for future studies:

- Although the indoor and outdoor lighting conditions represent many typical ambient lighting environments of construction workers, they do not represent all environments. Further studies are needed to test brighter environments, particularly in the southern U.S., where the sun has a higher elevation angle than in the upper Midwest. Also, darker environments must be tested, as sometimes workers must work in dimly lit conditions, such as predawn and at sunset.
- The contrast between the reference material (tan shingle) and the tool user's skin (light-colored Caucasian) was high, and the high sensitivity and specificity results may not be applicable to workers

with darker colored skin, such as Latinos, Asians and African-Americans. Many more combinations of substrates and skin color groups must be tested.

•The only clothing tested was a medium-colored denim material. Different color attributes and material patterns of shirt, pants and gloves must be tested. Color attributes include hues (e.g., red, blue, green, yellow), values (brightness of a hue), tints (lighter version of the hue, with white added) and shades (darker version of the hue, with black added). Clothing patterns include plain, striped, checked, plaid and spotted.

•The orientation of the shingle in the study was primarily horizontal and, thus, the shingle received most of the light from above. If the orientation of the substrate were vertical, the smart trigger system may not work as well due to less light from ambient sources and shadows created by the tool or the worker. Future studies must test different orientations of construction materials.

Conclusion

The chief advantage of integration of the smart trigger system into powered fastener tools is the potential to reduce the number of acute injuries to construction workers and consumers from accidental discharge, either through accidental firing or contact, without compromising the production rate of the CAT system. With the smart trigger system design, which compares image profiles of the intended substrate with other surfaces, the incidence rate of acute injuries from accidental discharge of fasteners would theoretically decrease. In addition, the cost of acute injuries would theoretically decrease, thereby reducing the cost to employers and workers' compensation systems.

The smart trigger system is in its early stage of development. More rigorous and expanded testing in the field with a much larger sample size (> 1,000 observations) is necessary before the system becomes commercially available. An expanded field test should include more combinations of lighting, skin color, clothing and construction materials. **PS**

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