

# TECHNOLOGICAL INTERVENTION TO ELIMINATE BACK INJURY RISKS FOR NAILING

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**ABSTRACT:** "Ergonomics" is derived from the Greek words "ergon," meaning work, and "nomos," meaning natural laws. Thus, one can interpret ergonomics as the "natural laws of work." As documented in the literature, ergonomics has long been ignored by management and workers in construction alike. Unfortunately, a sore back in the evening is not always the effect of healthy hard work at the jobsite made apparent by the staggering cost of workers' compensation. Occupational back injuries result in more lost workdays than any other illness, secondly only to the common cold. In addition, manufacturers of construction tools have started to redesign their products because of liability concerns. This paper describes an effort that considers the health epidemic of back injuries as an opportunity. The basic premise is to apply the "natural laws of work" in a scientific manner to reach and treat the root of the problem and not its symptoms. Pneumatic nailing of subfloors is used to explain that back pain and the risk of back injuries for the average construction worker can be decreased, while at the same time maintaining short-term productivity and increasing long-term productivity.

## INTRODUCTION AND BACKGROUND

A 1987 survey, involving 12 states, found that occupational back injury was the most frequent work-related disorder, accounting for 22% of all the reported cases and 32% of all workers' compensation dollars (*Federal Register* 1992). It has also been noticed that during the past decade, workers' compensation benefits have increased 157%, while employer costs have risen 143% (Nelson 1993). These costs are of concern to everyone because they encompass not only medical care but also lost productivity in the industry. It has also long been recognized that the greatest potential for low back pain prevention exists in the workplace (Pope et al. 1984) since incidence, severity, and potential disability are all related to the demands on the individual on the job.

A study reported by Bernold and Guler (1993) found that: "Experts in construction safety strongly believe that the major catalysts to back-related accidents are the poor fitness of workers as well as the weight and the bulkiness of the construction material today." On the other hand, back pain has afflicted man from the beginning of time; there is even evidence that primitive man suffered from some form of lower back disease. Backaches, as common as they are, are very rarely lethal, but statistics show that they cause an extreme amount of misery. The recurrent attacks of pain generally occur during a person's adult years, often interfering with the prime years of life.

The majority of the advances and understanding of back injuries have occurred in the last 20 years. Despite this fact, back pain has developed into man's most important non-life-threatening disease, while a detailed understanding of its causes and potential remedies continue to be elusive.

## Strength and Weakness of Spine

The spinal column is a unique part of the skeletal structure; it not only provides support for the body, but it also allows free movement of the upper trunk. Articulation is made pos-

sible by the spinal disks, the cartilage wafers tying each vertebra to its neighbor and by facet joints that link each vertebra. The disks act as shock absorbers that cushion loads and allow multidirectional movement to occur (*Stand* 1986). This movement is controlled by the contraction of muscles in the lower back and abdominal region. Ligaments support and strengthen the joints and prevent abnormal movement from occurring.

The spine is the only bony support for the body between the rib cage and the pelvic bones. As indicated in Fig. 1, the area just above the pelvis appears to be the most common site of injury in the lower back especially between L4 and L5. Lifting a concrete block causes both a vertical force and a moment, created by the weight of the block  $F_w$  and its distance from the body. While the load  $F_{bc}$  is transferred via the spinal column to the pelvis creating an evenly distributed compression in each disk, the moment results in an additional triangular stress component. The corresponding tension force  $T_m$  has to be carried by the muscles attached to the end of each vertebra. Fig. 2 presents stress-related deformations of a disk that can lead to a lasting or nonhealing damage. Small elements of a ruptured disk break loose, harden over time, and "work themselves" toward the spinal cord. Eventually, the "owner" of the ruptured disk will not only experience back pain but excruciating spasms in one leg or the other caused by an inflammation of nerve strand(s) that are being squeezed by the "breakaway" disk fragment. At this state, only a surgical intervention will bring relief to the injured person.

## Back Injuries in Construction

Workers in the construction field are exposed to a number of recognized occupational risk factors for back pain including heavy materials, pushing, twisting, frequent lifting over 65 lb, sudden unexpected shock forces, and a number of awkward postures (Bernold and Guler 1993; Pope et al. 1984). No two jobsites are ever exactly alike, and even the same jobsite changes on a daily basis. Because of this, it is much more difficult to study back injuries in construction than in an industrial setting.

A variety of possible approaches have been recommended to address back injuries generally leading to the development of technological and managerial interventions. These interventions include simple to more advanced engineering solutions (i.e., development of tools and lifting devices), administrative controls (e.g., on-the-spot corrections), and education and training (i.e., exercise sessions, and classes on proper lifting techniques). Each of these interventions involves ergonomics as a means to evaluate existing workplaces, jobs, and equipment to fit the worker.

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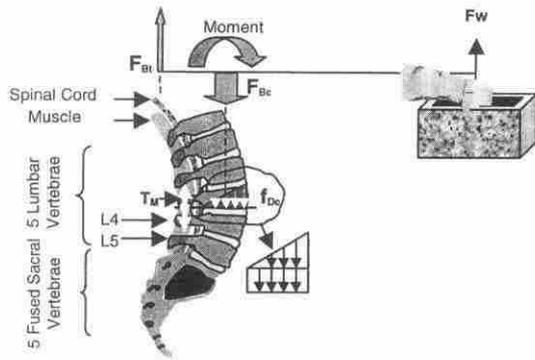


FIG. 1. Diagram of Forces and Stresses Experienced by the Spine

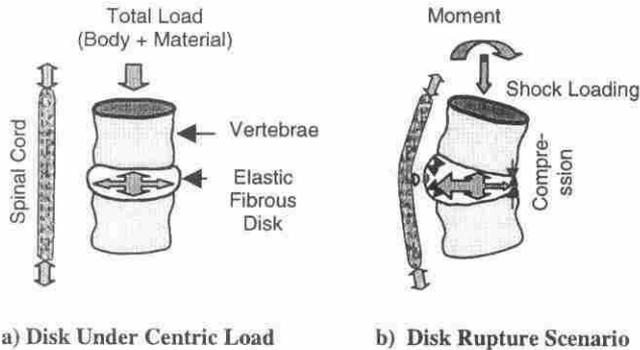


FIG. 2. Basic Mechanics of Deformation and Rupture of a Fibrous Disk

According to Bernold and Guler (1993), the number of back injuries in the low-rise residential construction business greatly exceeds the injuries incurred by workers in other construction sectors. Because of the importance of building construction, this paper will present work that has been done to study one operation that has been found especially abusive to the back—nailing subfloors with a nail gun.

### PROBLEM IDENTIFICATION AND ASSESSMENT

The monitoring of jobsite conditions began with a motion analysis of carpentry work on two residential construction sites; 15 experienced workers from framing subcontractors were involved in the study. Data were collected via continuous video analysis for the period of several workdays. The videotaping, done by North Carolina State University's Ergonomics Laboratory, encompassed the entire process of framing a residential home from beginning to end. This allowed for a better understanding of the biomechanical demands placed on the workers throughout all phases of the framing process. The technique used by the workers during each activity, such as their posture and the 3D force vectors was approximated and inputted into the 3-Dimensional Static Strength Prediction Program (3D-SSPP) for analysis (Mirka et al. 1998) as shown in Fig. 3.

Modeled in Fig. 3 are the postures of an average size male using a nail gun on the ground (side and oblique perspectives). The program calculated the external joint torque about L5/S1 joint as  $-1,223.4 \text{ in}\cdot\text{lb}$  ( $138.1 \text{ N}\cdot\text{m}$ ) and found that approximately 98% of the working population is strong enough to perform this task. Using this method of analyzing biomechanical stress it became apparent that other tasks were "back laboring" and induced extensive stresses into the back of a person of any size. From the generated list, six tasks were identified as the greatest contributors to low back "abuse." These tasks were

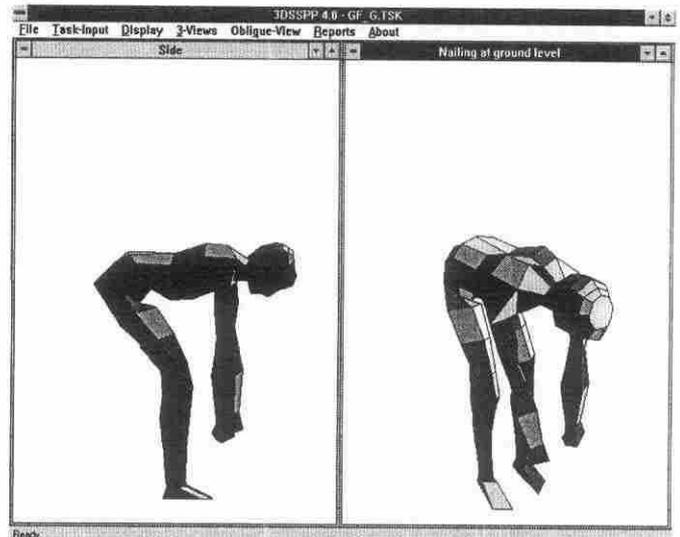


FIG. 3. Typical 3D-SSPP Diagram

1. Lifting raw materials from ground level
2. Working with power/air tools on ground level
3. Manually lifting trusses to the roof level
4. Carrying plywood flooring
5. Raising walls

The task of working with power/air tools on ground level was chosen for further analysis. In particular, the task of fastening plywood flooring to floor joists, otherwise referred to as subflooring, using a pneumatic nail gun became a focal point.

### Process Description

The subflooring operation starts with staging and cutting sheets of plywood. If cutting is needed, one of the three laborers fetches the plywood sheet from the stockpile and carries it to a sawhorse. Here, the plywood is marked and cut to its necessary shape before it is taken to the floor to be constructed and handed to a second laborer standing on the floor joists. He then carries the plywood to the location where it is needed and places it horizontally onto the floor joists. Using a rubber mallet the plywood is "guided" into position. The third laborer performs the fastening task generally with the help of a pneumatic nail gun. For this purpose he must bend over at the waist, position the tip of the gun with the safety mechanism using his right or left arm, fire the gun, and brace against the recoil of the firing mechanism.

### Quantitative Assessment of Stresses on Back

The trunk kinematics related to one-handed lifting, asymmetry, and load weight were the primary focus of intensive research performed at the Ohio State University's Biodynamics Laboratory (Allread et al. 1996). It was found that one-handed lifting, similar to that performed in the subflooring task, resulted in significantly higher ranges of motion in the lateral and transverse planes due to a coupling effect of bending and turning. For the purpose of assessing the actual stress that the nailing task exerts on the back a lumbar motion monitor (LMM) system was used. The LMM is a data collection device that allows the quantitative measurements of (1) the lumbar range of motion; (2) velocity; and (3) acceleration while a human is performing specific tasks. It acts as an exoskeleton of the spine that has been instrumented with sensors and fitted to the subject as shown in Fig. 4. The outputs of the sensors are transmitted to a personal computer which is



PC for Sensory Data Collection, Analysis, Risk Assessment, and Display  
Lumbar Motion Monitor Attached to the Back of the Test Person

FIG. 4. Experimental Work with Lumbar Motion Monitor

TABLE 1. Results of Lumbar Motion Test for Traditional Nailing

	LP	LV	LA	SP	SV	SA	TP	TV	TA
Traditional nailing	-4.9	5.5	26.7	66.9	6.4	28.8	-9.7	2.4	14.0

Note: L = lateral; S = sagittal; T = transverse; P = position (in degrees); V = velocity (in degrees/s); A = acceleration (in degrees per s<sup>2</sup>).

programmed to calculate the position, velocity, and acceleration of the lumbar spine during the activity. From these data points one is able to calculate stress distributions at crucial locations.

Three subjects were chosen to perform the task of nailing plywood sheets to floor joists in a controlled laboratory setting. All subjects were familiar with the use of the pneumatic nail gun and were of average stature for the male population. One experiment consisted of nailing two sheets of plywood to floor joists, each sheet requiring five rows with a minimum of four nails. Table 1 presents averages of all the conducted tests.

At 66.9°, the largest motion occurred in the sagittal position (SP), the forward bending of the trunk. At -9.4°, the transverse position (TP) represents a much smaller rotation of the trunk during bending. Due to the fact that the worker must extend one hand, the upper body has to rotate above the hip leading to the coupling effect discussed by Allread et al. (1996).

Since the video analysis of the site operations showed that the nailing of the subfloor is followed by the assembly and nailing of wall frames on the finished floor, the cumulative or repetitive effect of the coupled motion is significant. In addition, hand, arm, and upper body are also exposed to the recoil shocks of the firing mechanism. Thus, the stress analysis confirmed the earlier assessment of the research team, which had identified the operation of a nail gun in a bent-over posture a prime "candidate" leading to back injuries.

## DEVELOPMENT OF TECHNOLOGICAL INTERVENTION

It became immediately apparent that it was impossible to propose a redesign of the work setup since the plywood had to be nailed to the floor on which the nail gun operator had to stand. Instead, it was decided to find a mechanism that was capable of bridging the gap between the handle of a nail gun at floor level with the hand of an upright standing person. The resulting device was called the Ergonomic Nailing System (ENS).

One of the key requirements of the ENS was to attach it to

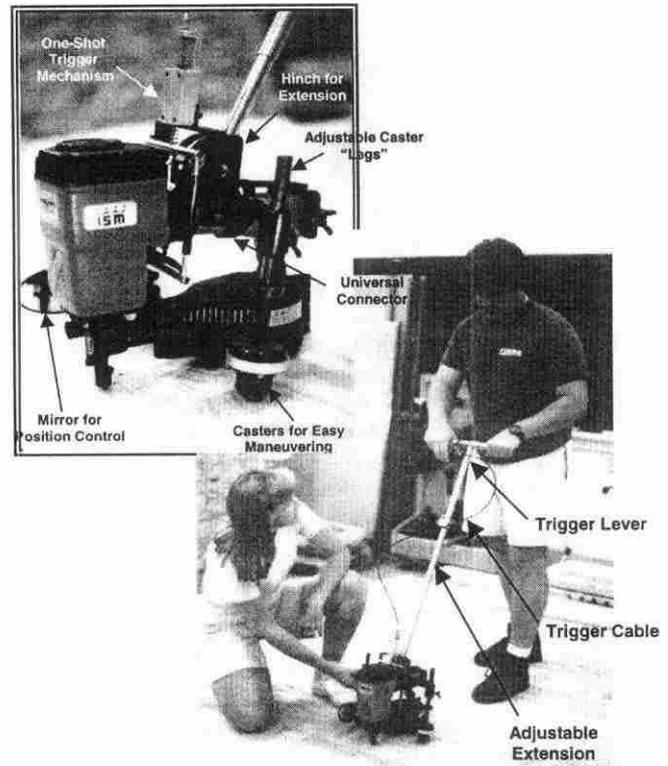


FIG. 5. ENS Prototype 1 Ready for Laboratory Testing

any commercially available pneumatic nail gun. For the first prototype, other features were considered:

1. Lightweight aluminum structure
2. Height and angle adjustment capability
3. Trigger operation at waist level
4. Mobility with the use of multidirectional, height adjustable casters
5. Safe operation by utilizing the safety mechanisms of the nail gun itself
6. Quick and efficient method of attaching and the detaching nail gun

The resulting first prototype, as pictured in Fig. 5, uses aluminum tubing for the fabrication of a manual extension and nail gun carriage that are adjustable in both height and angle. A trigger lever, located on the right handle grip, is connected to the mechanism that allows only one nail to be fired at a time and only when the nail gun is in the correct position for nailing. Thus, the ENS maintains all of the safety elements implemented by the manufacturers of nail guns. Height adjustable casters eliminate the need for carrying the load of the gun as well as the recoil effect on the arm and body.

After the design and fabrication of the ENS, the effectiveness of the innovative concept had to be tested concerning two critical issues: (1) strain on the back; and (2) productivity of nailing.

## ERGONOMIC COMPARISON

First, the controlled laboratory tests with the LMM were repeated, but this time with the ENS. The summary results of these tests are presented in Fig. 6.

As expected, the average trunk SP decreased drastically from 66.9° to 12.4°. In addition, the trunk TP (rotation of the trunk) was reduced from -9.7° to -4.4° but not totally eliminated. Both of these differences were statistically significant at the  $p < 0.0001$  level.

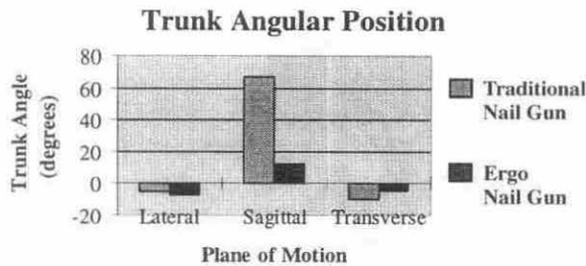


FIG. 6. Quantitative Impact of ENS on Bending

After analyzing the videotapes of the controlled laboratory testing and the accompanying LMM data, it was noted that the remaining trunk rotation was caused by the need to view the exact location of the gun tip before firing. To solve this problem, a mirror was mounted on the frame of the ENS. This mirror can be seen in Fig. 5(a).

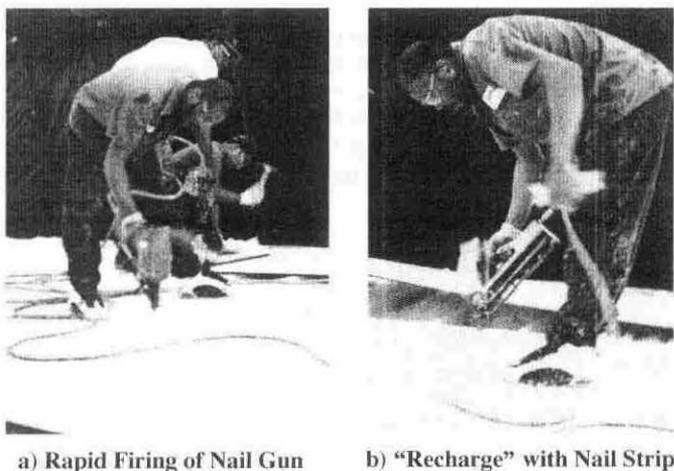
### COMPARATIVE FIELD TESTS

After the successful evaluation of the ENS in the ergonomics laboratory, field tests had to be conducted in order to quantify its productivity. A manufactured housing plant was chosen to compare traditional nailing with the ergonomic nail gun operation. In addition to the convenience of having a fixed and protected "construction site" available, the task of nailing plywood sheets to floor joists is performed by one worker alone, establishing the needed consistency. The initial observations of the process at the American Homestar Manufactured Housing Plant in Henderson, N.C., were made on May 29, 1998.

As can be seen in Fig. 7, the form and shape of the nail gun used at American Homestar is quite different from the one commonly used by homebuilders. Because the flexibility of the first ENS prototype was not sufficient to handle the difference, a second ENS prototype had to be designed.

### Assessment of Traditional Nailing

On June 1, 1998, the worker performing the subfloor-nailing task was observed and interviewed. The employee expressed concern for his health and admitted that the back-bending task of nailing had indeed taken its toll on him. This worker was filmed for three continuous hours in order to determine his productivity level. Random 3-min intervals were extracted from the video and analyzed. During each 3-min interval, the amount of time spent in various activities was noted. These activities were broken down into four task categories: (1) nailing; (2) loading nails; (3) talking; and (4) other nonessential



a) Rapid Firing of Nail Gun b) "Recharge" with Nail Strip

FIG. 7. Traditional Subfloor Nailing in Manufactured Housing Plant

TABLE 2. Results of 3-min Rating Using Traditional Method

3-min time slot	Nailing (s)	Loading nails (s)	Talking (s)	Other (s)
1	70	10	0	100
2	80	20	0	80
3	10	30	60	80
4	35	20	55	70
5	65	15	20	80
6	85	0	0	95
7	30	30	10	110
8	60	35	15	70
9	35	0	65	80
10	50	20	15	95
Average	52	18	24	86
Distribution (%)	29	10	13	48

tasks such as walking, standing, waiting, moving the air hose, removing tools, and readjusting the plywood. The results of the 3-min rating test are shown in Table 2.

As can be seen, the majority of the worker's time is spent in nonproductive tasks. In fact, he spent an average of 29% of his time on nailing and 10% on reloading, both in a bent-over posture. It would have been interesting to find out how much nonessential time he spent staying upright in order to reduce back pain, thus becoming essential to the nailing task.

Since manufactured housing fabrication is a linear operation where each process is on the critical path, nailing had to be "in-sync" with the processes that followed. The large amount of time the nail gun operator spent doing "other things" would provide a large time buffer for an eventual slowing of nailing speed with the ENS. Thus, it was decided to focus the future field tests on assessing the overall efficiency and user-friendliness of the ENS, rather than the amount of nails fired per minute.

### Redesign of ENS Prototype

The modifications to the initial design of the ENS were completed in early August 1998. As shown in Fig. 8, several features were added. To increase its versatility for work on building sites a swivel mechanism was added that allowed toenailing as well as the horizontal nailing of wall frames on the floor, and the larger guns used in manufactured housing required that the length of the legs be made slightly longer. The modified ENS prototype 2 was first taken to a building site to get feedback from an experienced carpenter, as shown in Fig. 9.

As observed many times before, the contractor liked the tool but was not willing to pay much for it. After this successful

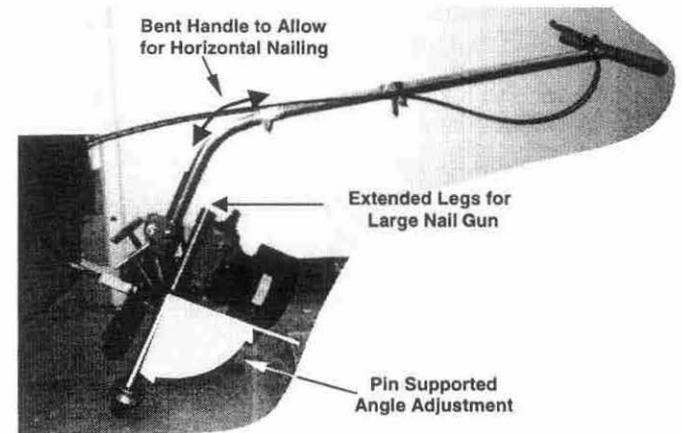


FIG. 8. ENS Prototype 2 with Added Capabilities



FIG. 9. Technical Testing of ENS Prototype 2 on Construction Site

technical feasibility test, ENS was ready to be tested at the manufactured housing plant.

### Comparative Assessment of ENS

It was expected that the nail gun operator at the American Homestar Manufactured Housing Plant would need some time to adjust, but, fortunately, this learning effect was minimal. After only a few minutes he was operating the device with ease (Fig. 10). Other workers and one foreman experimented with the ENS in order to satisfy their curiosity. Everyone was impressed with the maneuverability and speed of operation.

Once again, the videotape was reviewed in 3-min intervals to determine the worker's productivity level. The results of the 3-min rating are presented in Table 3.

The data from the time study indicate that the distribution of productive and nonproductive time did not change significantly. With the except of time slot 8, the time spent nailing during a 3-min period was comparable to traditional nailing. This outlier was caused by the difficulty in nailing around preinstalled pipes and electrical conduit protruding through the floor frame since the two casters were in the way. Hence, the operator had to spend extra time maneuvering the nail gun point to the proper position to fire the nail. It became clear

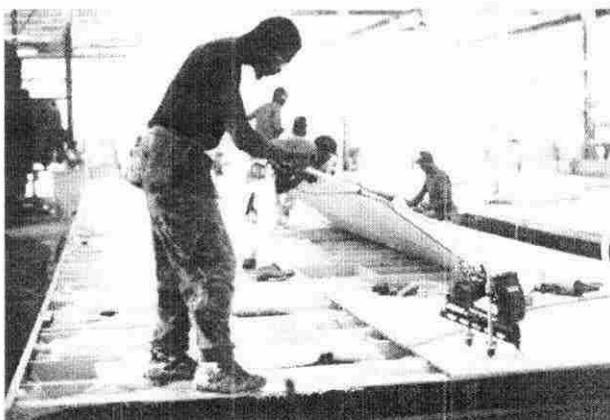


FIG. 10. Subfloor Nailing with ENS Prototype 2

TABLE 3. Results of 3-min Rating Time Study of ENS Prototype 2 Operation

3-min time slot	Nailing (s)	Loading nails (s)	Talking (s)	Other (s)
1	85	0	20	75
2	40	20	20	100
3	10	30	60	80
4	45	20	25	90
5	60	0	15	105
6	10	20	50	100
7	25	15	10	130
8	110	25	0	45
9	65	15	55	45
10	80	10	50	40
Mean	53	15	30	82
Distribution (%)	29	9	17	45

that small modifications to the carriage would be needed to add the needed flexibility.

The field tests with the ENS prototype demonstrated that reducing the risk of injuring one's back during nail gun operation will not result in lower productivity. On the contrary, the researchers feel confident that long-term experiments would show that the elimination of muscle-relaxing "back-straightening" activities would increase the productive time of a worker. Unfortunately, the funding limitation did not allow the test of this hypothesis.

### SUMMARY AND CONCLUSION

Occupational back injuries are on the rise, resulting not only in pain and suffering but also in staggering costs to the economy. Although it is not life threatening, it is life changing. The lack of a self-healing process can turn a human body into a self-contained "prison." This paper presented a technical intervention to the problem of pneumatic nailing of subfloors and wall panels in building construction—the ENS. After a short discussion of an ergonomic analysis of various building construction tasks, a thorough description was given of the innovative process that led to comparative tests of the ENS prototype. The basic concept is based on an extension that eliminates the need for the worker to bend and twist during operation. In addition, the ENS also absorbs the recoil forces of the firing apparatus.

The experimental tests in an ergonomics laboratory and in a manufactured housing plant demonstrated that (1) the system's basic mechanical concept is sound; (2) the coupled effect of bending and twisting on the human body is sharply reduced; and (3) nailing productivity is not significantly impacted. The data from the comparative time study in the housing plant also indicated that the slowdown due to learning is minimal.

### ACKNOWLEDGMENTS

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### REFERENCES

- Allread, W. G., Marras, W., and Parnianpour, M. (1996). "Trunk kinematics of one-handed lifting, and the effects of asymmetry and load weight." *Ergonomics*, 39(2), 322–334.
- Bernold, L. E., and Guler, N. (1993). "Analysis of back injuries in construction." *J. Constr. Engrg. and Mgmt.*, ASCE, 119(3), 607–621.

Bureau of Labor Statistics. (1995). "Workplace injuries and illnesses in 1994," *USDL-95-508*, U.S. Department of Labor.

*Federal Register*. (1992). (Aug. 3).

Mirka, G., Kelaher, D., Nay, T., Lawrence, B., and Reese, J. (1998). "Continuous assessment of back stress (CABS) in framers in the home building industry."

Nelson, W. J. (1993). "Workers compensation: Coverage, benefits, and costs, 1992." *Social Security Bull.*, 56(3), 68-74.

Pope, M., Frymoyer, J., and Andersson, G. (1984). *Occupational low back pain*, Praeger Publishers, New York.

*Stand, Lift, Carry*. (1986). Construction Safety Association of Ontario, Toronto.