HUMAN FACTORS, 1989, 31(3), 335–344

An Experimental Analysis of Railroad Spike Maul Methods

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This study investigated differences in railroad spike maul methods between experienced track workers and novice subjects. Differences were analyzed by developing a quantitative measure of the orientation of the spike maul path during spiking. The relationship between spiking motion pattern and spiking performance in both novice and experienced subjects was also investigated. Subjects were videotaped while using a spike maul on an instrumented spike force measuring system. Analysis of videotapes and performance measures revealed significant differences in motion patterns and performance between novice and experienced subjects. It was concluded from analysis of spike maul motion patterns that experienced track workers had developed a more efficient ballistic technique than had novices. This technique was evidenced by positioning of the maul close to the body's center of gravity, flexing the elbows, and using wrist motion on the downswing.

INTRODUCTION

Despite automation in the railroad industry, hand tools are widely used, especially for track maintenance. A recent study showed that 20 357 injuries in the railroad industry from 1975 through 1980 were attributed to the use of hand tools (Rockwell, 1982). Of railroad safety officers interviewed, 67% considered the spike maul to be the most hazardous tool in track work (Marras and Rockwell, 1986).

The spike maul is a striking tool similar to a sledgehammer but with a longer and thinner head. Used to drive railroad spikes, it weighs about 5.2 kg. Spike maul use requires swinging the maul over one's head, then hitting a spike. Marras and Rockwell (1986) reported that this requires the user to exert significant forces on the maul, whose center of gravity is a great distance from the user's trunk. Internal forces must be exerted by the user to balance the external force of the spike maul, which results in spine loading. When such loading occurs repeatedly over time, there is a possibility of cumulative trauma in the form of low back pain or injury.

Marras and Rockwell (1986) found that the method of spike maul use affected the components of spine loading (compressive, shear, and torsional loading components). The method of use was also found to affect spike-driving performance of novice subjects (Marras and Rockwell, 1986). Further study of spiking methods could lead to recommendations for spike maul training that would reduce the possibility of injury.

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Recent literature on hand tools focuses on the physical characteristics and mechanical factors of hand tools rather than methods of using the tools. Furthermore, the literature has concentrated on small hand-held tools, such as pliers and screwdrivers. Garrett (1971) presented data on biomechanics and engineering anthropometry of the hand which are especially useful in the design of small hand-held tools. However, such data are not adequate for the study of heavier hand tools, such as the spike maul, which require gross body movements.

Recommendations for the design of hand tools by Greenberg and Chaffin (1982) could apply, in some cases, to spike maul design. For example, those authors recommended providing places for both hands to grasp a heavy tool and as great a force-bearing area as possible for tools to be gripped in the palm. These criteria are met with the present design of the spike maul.

Recent studies on striking tools have addressed mechanical factors in the design and use of the tools but not the issue of methods of tool use. In a study by Drillis, Schneck, and Gage (1963), the theory of striking tools was discussed in terms of efficiency. They defined tool efficiency as the ratio of energy utilized to energy available based on the laws of mechanics. Widule, Foley, and Demo (1978) and Corrigan, Foley, and Widule (1981) evaluated several axe designs in terms of kinetic energy of the tool during the axe swing and physiological costs of axe use. Results showed that a heavy axe had a mechanical advantage over other axe designs but that physiological cost (measured by heart rate) was greatest with the heavy axe. This finding demonstrates the importance of considering the effects of tool use on the user in addition to the mechanical design of the tool.

Few studies have specifically addressed methods used with large hand tools in terms of gross movements of tools and users' bodies. Therefore, the present study was conducted to investigate further the role of methods in the use of heavy hand tools.

Objectives

The main hypothesis of this study was that experienced track workers have developed a spiking method that differs significantly from the method used by novices and is more efficient, resulting in increased performance.

Our main objective was to investigate the differences between experienced and novice subjects by developing a quantitative measure of the shape and orientation of the spike maul's path during spiking. A second objective was to determine how these measures of spiking motion pattern relate to spiking performance in both novice and experienced track workers.

METHOD

Subjects

Twenty men—15 college students and 5 experienced railroad track workers—served as subjects. Height, weight, dynamic strength tests, and several other anthropometric measurements were taken on each subject. Waist depth, waist circumference, upper arm circumference, lower arm length, and upper arm length were measured. Arm strength was measured with a Cybex II isokinetic dynamometer. Maximum torque exerted during shoulder extension and elbow flexion was measured at speeds of $\pi/3$, π, and $4/3\ \pi$ radians/s as described by Lumex, Inc. (1983). Several derived and composite strength measures were calculated: (1) normalized torque (normalized by dividing by arm length or lower arm length), (2) slope of torque and normalized torque against speed, and (3) average maximum torque and normalized torque (averaged over the three speeds tested). Dynamic back strength was measured on a Mini-Gym, Inc., Super 2 Strength/Fitness System.

Analysis of variance showed significant differences between experienced and novice subjects in age, $F(1,18) = 10.7$, $p < 0.01$; upper arm length, $F(1,18) = 8.9$, $p < 0.01$; slope of elbow torque versus speed, $F(1,17) = 4.8$, $p < 0.05$; and slope of normalized elbow torque versus speed, $F(1,17) = 6.2$, $p < 0.05$. Table 1 contains descriptive statistics on these and other selected measures.

Experimental Design

A one-way analysis of variance (ANOVA) model with two levels of experience was used. The independent variable—experience—had two levels: novice and experienced track workers. The dependent variable—spike-mauling motion pattern—was measured as described in detail later in this report. The design was unbalanced, with 15 novice and 5 experienced subjects.

Three other dependent variables were also measured, all performance measures of spike forces on hitting a spike: vertical spike force, spike-driving force, and accuracy. Multiple linear correlation analysis was used to relate these performance measures with the spike-mauling motion pattern. A second ANOVA model was used to investigate the effects of experience and practice on vertical spike force. A two-way model with interaction, two levels of experience, and three levels of practice (first, second, and third sets of ten hits on the spike) was used.

The spike force measures were defined as follows: vertical spike force (Z) was defined as average force (measured in newtons) on the spike in a direction perpendicular to the ground. Spike-driving force was defined as average peak resultant force of orthogonal X, Y, and Z components on the spike as shown in Figure 1. The spike-driving force was defined as follows:

$$SP = (X^2 + Y^2 + Z^2)^{1/2} \quad (1)$$

Accuracy was defined as the ratio of vertical spike force to spike-driving force and was defined as

$$AC = \frac{Z^2}{X^2 + Y^2 + Z^2} \quad (2)$$

TABLE 1

Selected Subject Characteristics

Characteristic	*Experience*	*N*	*Mean*	*SD*	*Minimum*	*Maximum*
Age (years)	Track worker	5	29.2	6.2	23.0	38.0
	Novice	15	23.3	2.2	20.0	27.0
Height (cm)	Track worker	5	178.8	1.1	177.8	180.3
	Novice	15	178.8	7.0	167.6	195.6
Weight (kg)	Track worker	5	77.5	9.8	65.7	90.6
	Novice	15	78.0	12.1	63.4	106.5
Upper arm length (cm)	Track worker	5	33.4	2.2	31.6	37.2
	Novice	15	36.5	1.9	34.0	41.8
Slope of elbow torque versus speed	Track worker	5	−0.07	0.01	−0.08	−0.06
	Novice	14	−0.05	0.01	−0.08	−0.04
Slope of normalized elbow torque versus speed	Track worker	5	−0.0027	0.0007	−0.0038	−0.0021
	Novice	14	−0.0019	0.0005	−0.0026	−0.0012
Experience (years)	Track worker	5	7.0	3.9	3.0	14.0

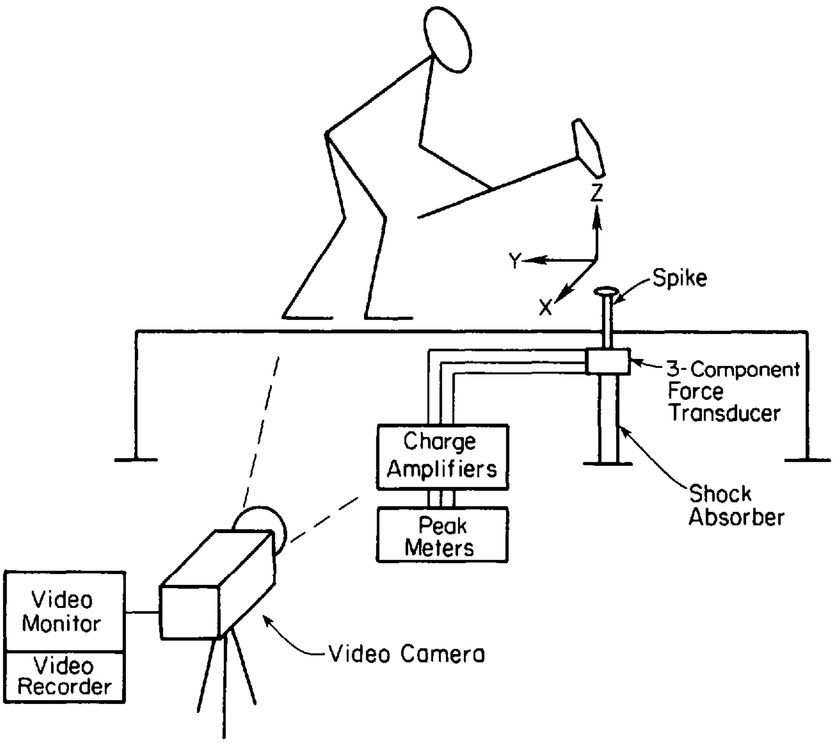

Figure 1. *Instrumented spike force measurement system and video equipment.*

Apparatus

The experimental apparatus was an instrumented spike force measurement system used in previous studies of railroad hand tools (Marras and Rockwell, 1986; Rockwell and Marras, 1986). This system measured three orthogonal force components applied to a railroad spike during spike insertion or removal. Figure 1 illustrates the apparatus. The spike was attached to a three-component force transducer and mounted on a shock absorber. The purpose of the shock absorber was to simulate the resistance in driving a spike into a wood railroad tie (approximately 482 kPa), The force transducer measured incident forces on the spike during spiking.

Three charge amplifiers and peak-hold meters conditioned the transducer output signal and displayed a maximum voltage each time the spike was hit. Peak meter voltages were recorded after each hit.

Subjects were videotaped (side view) while driving the spike. The spike maul used in this experiment was a 5.8 kg Bop Hammer, a spike maul with lead shot enclosed in its head to transfer momentum on striking a spike. Being slightly heavier than standard spike mauls, it was chosen for its durability.

Procedure

Data on railroad track experience, health history, and anthropometric measurements were collected from the subjects before testing. Subjects practiced hitting the spike on the force measurement system until comfortable with the task. For testing subjects were instructed to hit the spike once with the spike maul and then to pause. Three separate trials of ten single hits were performed by each subject. Between each set of ten hits the subjects were given a five-minute rest break. The spike force components were recorded from the peak meters for each hit. Each hit was videotaped. The subjects and experimenter wore safety glasses and protective helmets during testing.

Spiking Motion Analysis Procedure

Figure 2 summarizes the spiking motion analysis procedure. Subjects' motion patterns during the spike maul task were analyzed in terms of rotation of the spike maul around the shoulder. The side view videotapes were analyzed for each subject. The motion pattern during the swing of the spike maul that resulted in the highest vertical spike force for each subject's final set of ten hits was analyzed. The landmarks of shoulder and maul head position were recorded from a video monitor at 10 to 15 approximately equidistant points through the swing. The subjects' shoulders were marked with white adhesive tabs to aid tracking of shoulder movement. Figure 3 shows a typical shoulder and spike maul motion pattern for an experienced track worker. The movement of the spike maul was then isolated around the shoulder by locating each shoulder point from the plot at the origin of a pair of two-dimensional coordinate axes, then plotting the maul head position relative to the origin. An example of these plots for an experienced subject is shown in Figure 4.

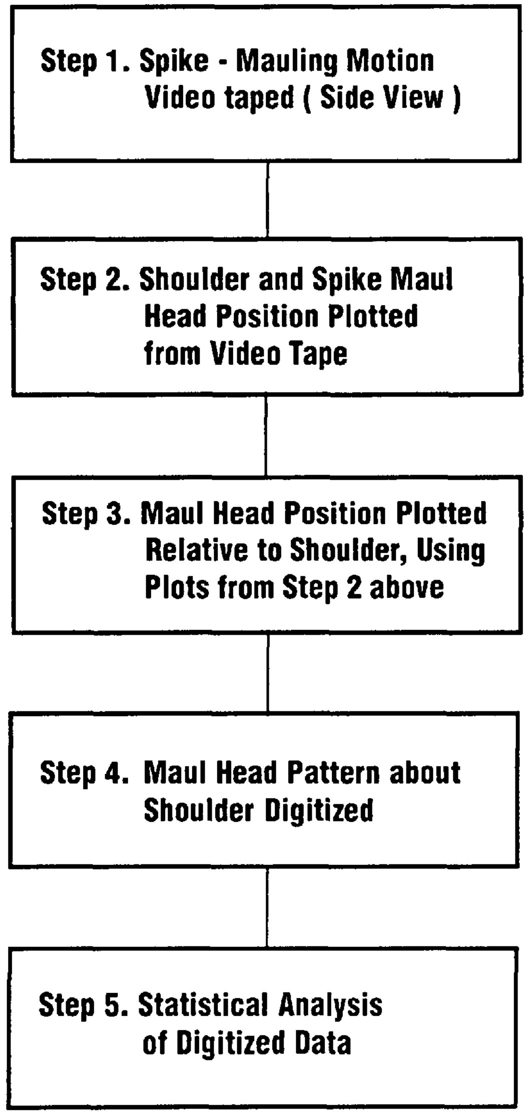

Figure 2. *Treatment of data from spike maul motion analysis.*

The spike maul motion patterns around the shoulder were then electronically digitized in two dimensions with respect to an arbitrarily chosen origin. A Bendix Datagrid Digitizer was used. Figure 5 illustrates the digitized plot of an experienced track worker's spiking motion and Figure 6, the plot of a novice's motion. Distance between digitized points is in centimeters but represents relative, not actual, distance.

There was a difference in orientation and slope of the digitized motion between experienced subjects and novices. The motion patterns for novices tended to be more circular than those of experienced track workers. In order to measure quantitatively the differ-

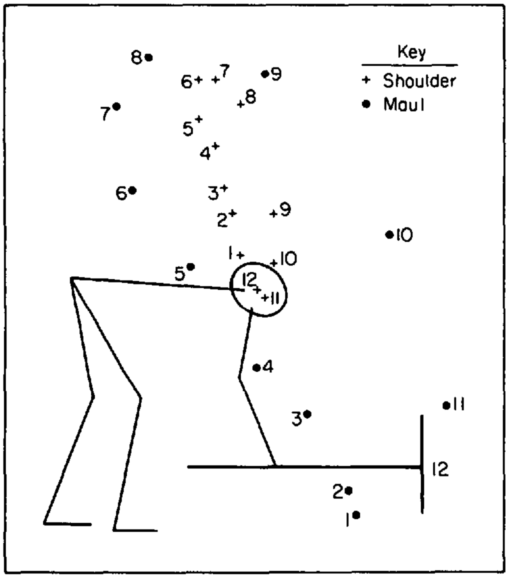

Figure 3. *Sample spiking motion pattern of an experienced track worker.*

ences in orientation of the motion pattern plots, a regression line was fitted to each subject's digitized spiking pattern. The slope of these regression lines gives an indication of the orientation of the spike maul path plots.

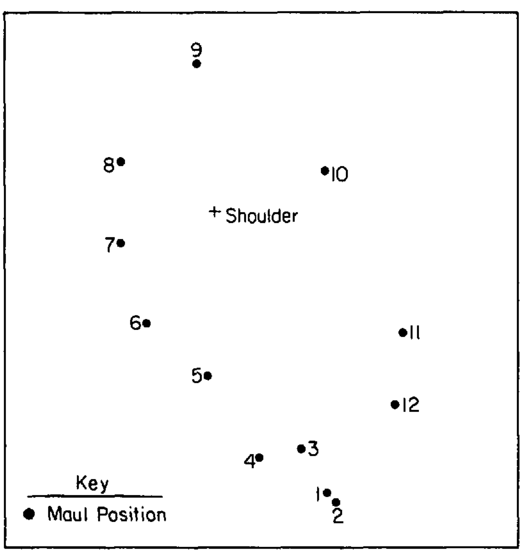

Figure 4. *Example of motion of spike maul around the shoulder of an experienced track worker.*

RESULTS

Descriptive statistics for regression line slopes describing spike-mauling motion patterns are given in Table 2. Means of the slopes are larger negatively for experienced track workers than for novices. Analysis of variance showed a significant difference between regression line slopes of novice and experienced subjects' motion plots, $F(1,18) = 12.28, p < 0.01$. Figure 7 illustrates the significant differences in mean slopes. Multiple linear correlation analysis showed the slope of motion plot regression lines to be negatively correlated with spiking performance measures of vertical spike force, spike-driving force, and accuracy. These correlations were significant ($p < 0.05$) for the group of experienced track workers (see Table 3) but not for the novice group alone.

Figure 8 shows how vertical spike force differed between groups and improved with practice for both levels of experience. As expected, experienced track workers reached higher vertical spike forces than did novices. Spike force levels for both groups improved over the 30 hits; analysis of variance showed experience and practice effects to be signifi-

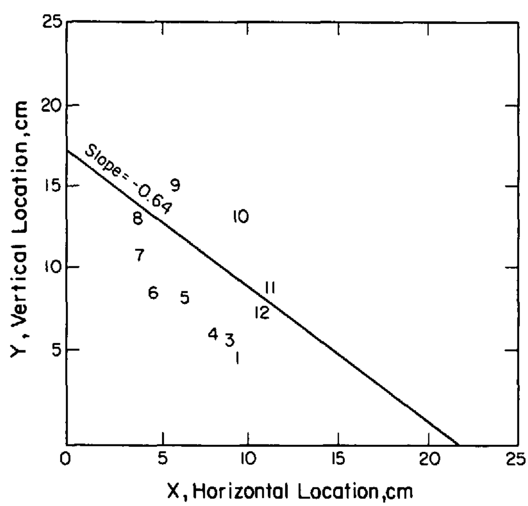

Figure 5. *Digitized plot of spike maul path around the shoulder of an experienced track worker.*

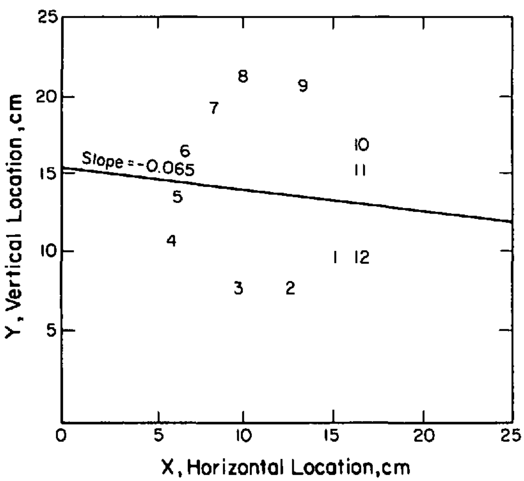

Figure 6. *Digitized plot of spike maul path around the shoulder of a novice subject.*

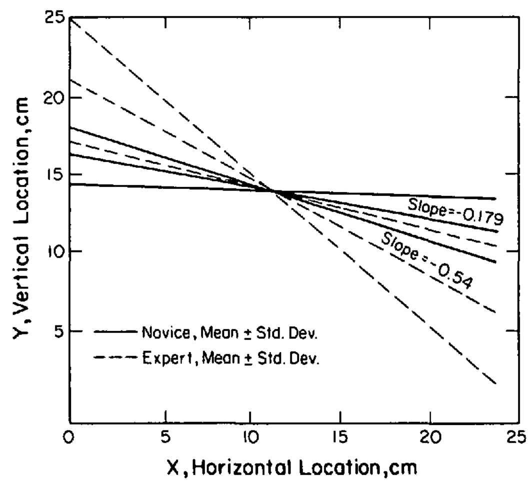

Figure 7. *Comparison of maul path regression line slopes for novice and experienced subjects.*

cant ($p < 0.05$). A two-way model with interaction, two levels of experience, and three levels of practice (first, second, and third sets of ten hits on the spike) was used. Table 4 illustrates these ANOVA results.

DISCUSSION

Results suggest that spike maul motion patterns are related to both experience level and force applied to the spike. The motion pattern differences between novices and experienced track workers seem to result from the following factors, which were noted during videotape analysis. For novices, the shape of the side-view maul path was circular because the subjects almost fully extended their arms throughout the swing. Experienced track workers, however, appeared to flex their arms at the elbow, bringing the maul close to their trunk during the upswing, and appeared to use more wrist motion on the downswing. This results in the elliptical maul patterns representative of the experienced group.

Studies have shown that elbow flexion is important for tasks in which the forearm and hand are rotated (Chaffin and Anderson, 1984, pp. 341–343). Elbow flexion provides a mechanical advantage for the biceps brachii muscle to rotate the forearm. Given that spike mauling requires forearm and hand rotation, it is possible that experienced track workers have adopted the practice of elbow flexion in order to capitalize on the mechanical advantage it provides.

A possible explanation for the differing motion patterns of novice and experienced subjects is that the track workers have devel-

TABLE 2

Descriptive Statistics for Maul Path Regression Line Slopes

Experience	*N*	*Mean*	*SD*	*Minimum*	*Maximum*
Novices	15	−0.179	0.15	−0.612	−0.034
Experienced track workers	5	−0.540	0.31	−0.955	−0.097

oped a more efficient ballistic spike maul technique than have novices. The experienced group's method would be more efficient in a number of ways. Not extending the arms fully throughout the swing would allow close control of the spike maul because it would be kept close to the body's center of gravity; this would also reduce spine loading by shortening the length of the moment arm from the spike maul head to the lower back. Elbow flexion would also aid in forearm and hand rotation, as noted earlier. On the downswing, wrist motion could increase momentum of the maul head, resulting in more force on the spike with less effort than if the motion were more controlled. This ballistic nature of the downswing of experienced track workers would allow great forces to be exerted on the spike with relatively little muscular control of the heavy spike maul. For experienced track workers, it appears that once the maul is positioned for the downswing, the task is ballistic, requiring little controlling effort (just snapping the wrist) to guide the maul to the spike and hit it. Thus their method takes advantage of gravity and the weight of the maul head to drive the spike.

Several other ballistic activities such as swinging a golf club or a baseball bat follow the same principle the experienced track workers seem to follow when swinging the spike maul: use of the tool's weight to build momentum with loose or little control in order to achieve greater force on the object

TABLE 3

Correlations between Maul Path Regression Line Slopes and Dependent Variables (Experienced Subjects)

Dependent Variable	*Correlation Coefficient*
Vertical spike force (*Z*)	−0.898*
Spike-driving force (*SP*)	−0.894*
Accuracy (*AC*)	−0.829

*$p < 0.05$.

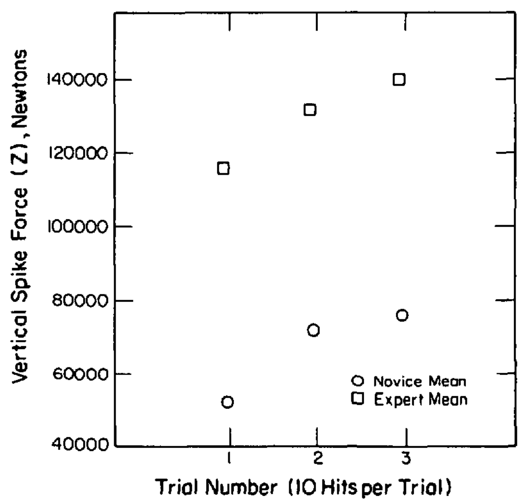

Figure 8. *Vertical spike force (Z) as a function of trial number showing group means.*

being hit. Track workers could be trained to make their spike maul swing more ballistic, just as baseball players and golfers are trained to improve their swings. Although this study did not address the grip of the hands on the spike maul, the amount of grip force exerted might be a factor in performance.

Another factor that could have affected the spike-mauling efficiency of experienced track workers is that they appear to bend their knees more than do novices on the downswing of the maul. This would cause subjects to get closer to the ground, allowing easier vertical positioning of the maul head at impact and maximizing useful spike-driving force.

Marras and Rockwell (1986) noted performance differences in ballistic maul-swinging arising from variation in the size of striking area. As tool striking area increased, control movements could decrease, allowing a more ballistic swing. Ballistic swinging also provided insight into spike-mauling method differences between novice and experienced track workers in that study: novices could exert more force on the spike when using a

TABLE 4

Analysis of Variance Results for Vertical Spike Force (Z)

Source	*Sum of Squares*	*df*	*Mean Square*	*F*
Model	5.16×10^{10}	5	1.03×10^{10}	16.76**
Experience	4.53×10^{10}	1		73.62**
Set = 10 Hits	4.54×10^{9}	2		3.69*
Experience × Set	1.77×10^{7}	2		0.01
Error	3.32×10^{-10}	54	6.15×10^{8}	

* $p < 0.05$, ** $p < 0.01$.

back-motion-only method, which required compensation for only one axis of rotation of the body. Hand positions on the maul which required less precise control motions resulted in greater spike forces. The present study showed that experienced track workers' maul path around the shoulder can be explained in terms of use of a highly ballistic swing.

Novice track workers could be trained to use the theoretically more efficient ballistic motion patterns exhibited by the experienced track workers in this study. The technique of bending the knees on the downswing could also be taught. The technique of "squaring up" with the spike before the downswing, as exhibited by experienced track workers in a previous study (Marras and Rockwell, 1986), could also be taught to novice track workers. In that study it was noted that experienced subjects aligned the spike maul and spike with the sagittal plane of the body; this would reduce the amount of muscular control needed to guide the spike maul. Training in the foregoing techniques could increase the efficiency of newly hired track workers and could also decrease injuries.

There is a possibility that the wrist-snapping techniques used by the experienced track workers, along with vibration and deviated wrist positions inherent to spike mauling, could contribute to cumulative trauma disorders of the hands. The trade-off between the efficiency of the wrist-snapping techniques and the development of carpal tunnel syndrome or other cumulative trauma disorders warrants further study.

CONCLUSIONS

A quantitative measure of motion patterns used in driving railroad spikes with a spike maul was developed. The measure used was the slope of the regression line describing the orientation of the path of the spike maul head around the subject's shoulder. Significant differences in this measure were found between experienced track workers and novices. Spike maul motion patterns were found to be related to performance in terms of vertical force applied to a spike for experienced workers but not for novices. A major difference found in spike maul technique between experienced subjects and novices was the wrist-snapping action used by experienced track workers on the downswing.

Further research should address the possibility of repetitive trauma disorders arising from extensive wrist motion during spike maul use by experienced track workers. Research into the training of new track workers according to the theoretically more efficient ballistic spike maul methods of the experienced track workers should be conducted.

ACKNOWLEDGMENTS

The authors wish to thank the Association of American Railroads for their support in this research and for the use of their equipment. The assistance of Nancy Gardiner with the pilot study for this research and of Cedric Cze with the experimental apparatus is also appreciated. Research for this paper was conducted at Ohio State University, Columbus, Ohio.

REFERENCES

Chaffin, D. B., and Anderson, G. (1984). *Occupational biomechanics*. New York: Wiley.

Corrigan, D. L., Foley, V., and Widule, C. J. (1981). Axe use efficiency, a work theory explanation of an historical trend. *Ergonomics, 24*, 103–109.

Drillis, R., Schneck, D., and Gage, H. (1963). The theory of striking tools. *Human Factors, 5*, 467–478.

Garrett, J. W. (1971). The adult human hand: Some anthropometric and biomechanical considerations. *Human Factors, 13*, 117–131.

Greenberg, L., and Chaffin, D. B. (1982). *Workers and their tools*. Midland, MI: Pendell.

Lumex, Inc., Cybex Division (1983). *Isolated-joint testing and exercise, handbook for using Cybex II and the UBXT*. Konkonkome, NY: Author.

Marras, W. S., and Rockwell, T. H. (1986). An experimental evaluation of method and tool effects in spike maul use. *Human Factors, 28*, 267–281.

Rockwell, T. H. (1982). *An evaluation of hazards in the use of railroad portable hand tools: Phase I report*. Columbus, OH: R & R Research, Inc.

Rockwell, T. H., and Marras, W. S. (1986). An evaluation of leverage hand tools in the railroad industry. *Human Factors, 28*, 303–315.

Widule, C., Foley, V., and Demo, G. (1978). Dynamics of the axe swing. *Ergonomics, 21*, 925–930.