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Effects of Handle Angle and Work Orientation on Hammering: I. Wrist Motion and Hammering Performance

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This research investigated the range of wrist motion characteristics associated with the ergonomic principle of "bending the tool and not the wrist" as applied to the hammer. It is thought that bending the tool reduces angular wrist motion, which has been shown in the literature to be a risk factor in hand/wrist disorders such as carpal tunnel syndrome and tenosynovitis. Hammer handles angled at 0 (straight), 20, and 40 deg were investigated in this study. For novices, hammer handles bent at 20 and 40 deg resulted in less total ulnar deviation than straight hammers. However, there was a trade-off in beginning and ending positions of the wrist in that the angled hammers reduced ulnar deviation at the impact position but increased radial deviation at the starting position of a hammer stroke. Handle angle did not significantly affect hammering performance. Wrist motion was affected minimally by hammering orientation, but hammering performance was significantly worse in the wall orientation compared with the bench orientation. This research suggests that for novice users, hammers with handles bent in the range of 20 to 40 deg could possibly decrease the incidence of hand/wrist disorders caused by hammering.

INTRODUCTION

This research concerns the hammer and how changes in its tool and task design affect the occupational biomechanics and safety of its users. According to the Ohio Industrial Commission (1985, 1986), the hammer or sledgehammer accounted for 14.2% and 19.1% of all hand tool injuries suffered by Ohio carpenters in 1985 and 1986, respectively. These injuries resulted in an average loss of 13.3 and 8.8 workdays, respectively. Most injuries were instantaneous trauma: cuts, contusions, fractures, and punctures. However, carpal tunnel syndrome, wrist tendon disorders, inflammation and irritation of the wrist, and wrist strains have been recognized as a growing problem in industry, and they collectively accounted for 12.5%, 12.5%, and 5.3% of all injuries caused by the hammer in 1984, 1985, and 1986, respectively (Ohio Industrial Commission, 1984–1986). These types of injuries could be broadly defined as cumulative trauma disorders (CTDs).

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In order to reduce the incidence of CTDs of the wrist, hand tools should be designed to minimize the amount of flexion/extension (palm/backside of hand) and radial/ulnar deviation (thumb/little finger side) of the hand (Armstrong, 1983; Greenberg and Chaffin, 1977; Tichauer, 1978). This has led to the ergonomic principle that it is better to bend the tool and not the wrist (Tichauer, 1978).

The reason for bending the tool and not the wrist is that when the wrist is not in a neutral position relative to the forearm, the tendons of the extrinsic forearm muscles compress against each other, the carpal bones, and the flexor retinaculum. This compression increases the interstructural forces and friction among the tendons, which can result in discomfort, early fatigue, and wrist diseases (Tichauer, 1978).

With regard to a conventional straight hammer, the wrist is snapped in the radial/ulnar plane to generate high driving forces. The snapping of the wrist could result in excessive ulnar deviation, which could cause DeQuervain's disease or tenosynovitis (Armstrong, 1983; Armstrong, Foulke, Joseph, and Goldstein, 1982; Damon, 1965; Meagher, 1986).

The concept of bent handles has been applied to hammers and investigated in several studies (Knowlton and Gilbert, 1983; Konz, 1986). Overall, the existing devices that measure wrist motion present practical problems that make it difficult to do a quantitive ergonomic assessment of tools with angled handles.

The theoretical basis for bending handles is well established, but research on the occupational benefits of tools with angled handles lacks quantification. A study that measures quantitatively how hammer handle angle and hammering orientation jointly affect wrist motion and hammering performance is needed to determine if there is an optimal handle angle and orientation that could possibly reduce the incidence of hand/wrist CTDs.

METHOD

Subjects

Eight healthy, right-handed men volunteered to be unpaid subjects in this study. All subjects were novices at hammering and had no hand or wrist injuries. The subjects' ages ranged from 23 to 29 years, with a mean of 24.6 years. Their mean height and weight were 181 cm and 77.3 kg, with standard deviations of 7.6 cm and 13.9 kg, respectively.

Experimental Design

Hammer handle angle (0, 20, and 40 deg) and hammer orientation (bench and wall) were the two independent variables in this study. The six possible conditions are shown in Table 1, and each subject hammered in all six conditions.

The dependent variables were divided into two groups: wrist position and hammering performance. All wrist angles were defined relative to the forearm. For the wrist position data, *windup* was defined as the position of the wrist at the beginning of a hammer stroke. *Impact* was defined as the position of the wrist when the hammer hit the spike.

The wrist motion dependent variables were (1) wrist radial deviation and extension at windup, (2) wrist ulnar deviation and flex-

TABLE 1

Experimental Conditions

Work Orientation	*Hammer Handle Angle (deg)*		
	0	20	40
Bench	X	X	X
Wall	X	X	X

ion at impact, and (3) joint angular range of motion (ROM) of the wrist in the radial/ulnar plane and in the flexion/extension plane.

The hammering performance dependent variables were driving force, accuracy, and number of misses.

Apparatus

Hammers. Each hammer was designed on an IBM CATIA 3-D system and built in the Biodynamics Laboratory at Ohio State University. Each hammer was constructed of 21-ply Baltic birch plywood and fitted with a head from a Stanley 16-ounce hammer (Model 51-616). Figure 1 shows the size, shape, and specifications of the hammers. The physical parameters of weight, center of mass, length of handle, flare, and cross-sectional shape and circumference were all tightly controlled.

Hammering fixture. The hammering fixture and setup are shown in Figure 2. The hammering fixture consisted of a wood structure that housed a spike fixture, a load cell, and an air shock absorber. The hammering fixture was oriented in both the wall and bench positions, as shown in Figure 2, and was similar to the fixture used in a spike maul study (Marras and Rockwell, 1986).

The spike fixture consisted of a machined cylinder in which tapered railroad spikes were placed and tightened by set screws. The railroad spikes were tapered to a 0.8-cm diameter head, which is the size of a 16d nail head. Spikes were replaced after each hammering session.

Wrist monitor. Wrist angle was measured by a wrist monitor, shown in Figure 3. The wrist monitor is a small electromechanical device that straps to the subject's wrist and records wrist angle in the radial/ulnar and flexion/extension planes. The wrist monitor has two lines connected to rings around the subject's index and ring fingers. As the wrist moves, these lines turn two potentiometers. The voltages from the potentiometers are used to calculate wrist angles. Calibration tests have indicated that this device is accurate to ±2.5 deg when 25 wrist measurements are taken during a task (Schoenmarklin and Marras, 1987).

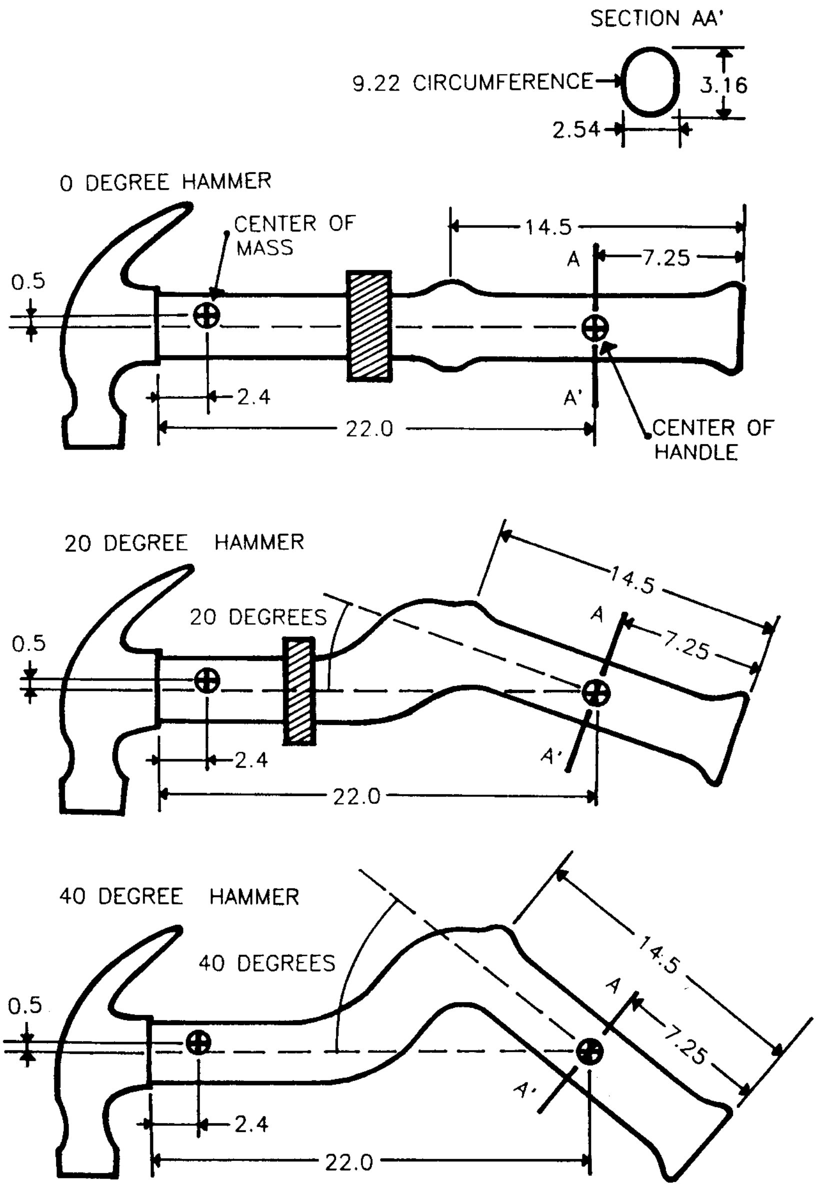
Procedure

Before the experiment each subject was briefed on its general objectives. Each subject hammered with the three experimental hammers in a practice session 30 min before the experiment. The subject then filled out a consent form approved by the Ohio State University Human Subjects Review Committee. Anthropometric dimensions of each subject's body and hand were documented.

Before the wrist monitor was attached, marks were placed on the bony landmarks of each subject's forearm and hand for alignment in the neutral position, as illustrated in Figures 4a and 4b. In the literature related to microgravity environments, the word *neutral* means the posture of least muscular strain. In each plane, when all three marks lie on an imaginary straight line, the wrist is in the physiologic neutral position with respect to the forearm.

The wrist monitor was strapped to the subject's wrist. The subject's forearm was securely strapped to the calibration table illustrated in Figure 5, and the wrist monitor was calibrated by collecting voltage data while the subject moved his wrist to specific locations in the radial/ulnar plane, flexion/extension plane, and four quadrants of wrist position.

The height of the hammering fixture was adjusted so that the subject's right arm was at a 45-deg angle to the hammering fixture, as shown in Figure 2. The subject then donned a hard hat and goggles. The experimenter instructed the subject to strike the



HAMMER SPECIFICATIONS:
WEIGHT = 640 GRAMS
WOOD = BALTIC BIRCH 21 PLY LAMINATE
HAMMER HEADS FROM STANLEY 16 OZ HAMMERS (51-616)

Figure 1. *Dimensions and specifications of straight and angled hammers used in study. All dimensions are in cm. The shaded areas represent extra weight to equalize the total weights of all three hammers.*

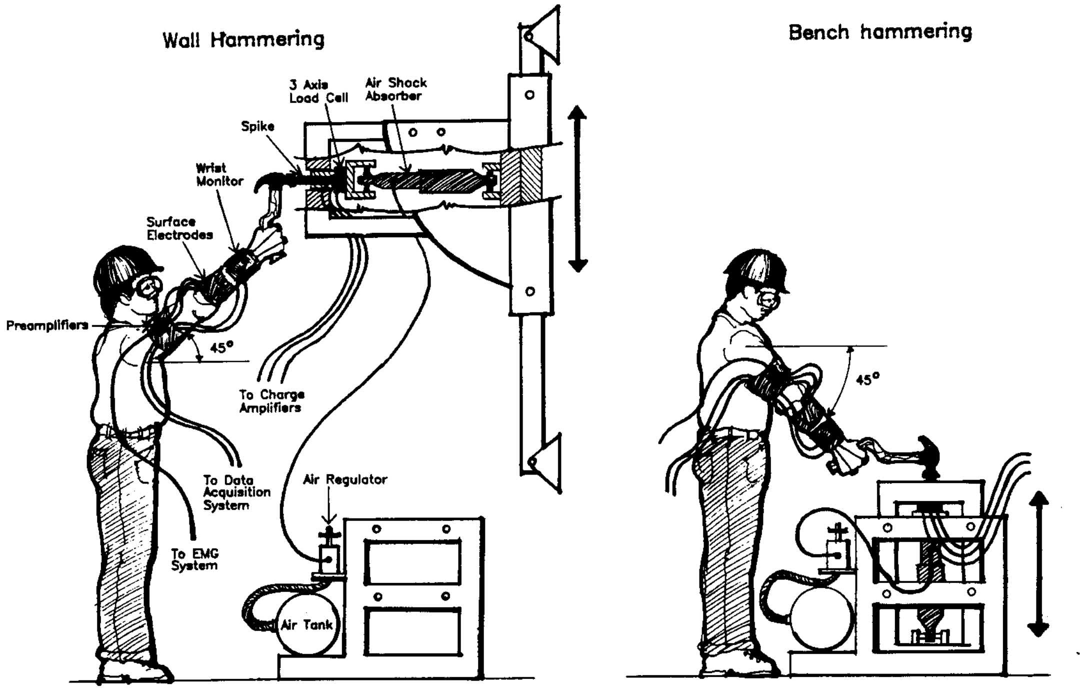


Figure 2. *Hammering orientations and apparatus used in study.*

spike as if he were hammering 16d nails into two-by-fours. The subject was instructed to hammer at the same cadence (57 strikes/min) as an electronic beeper placed near him. The subject hammered for three minutes in each condition.

Treatment of Dependent Measures

Driving force. The force data from the three-axis load cell were recorded and treated according to the diagram in Figure 6. The voltages displayed on the peak meters

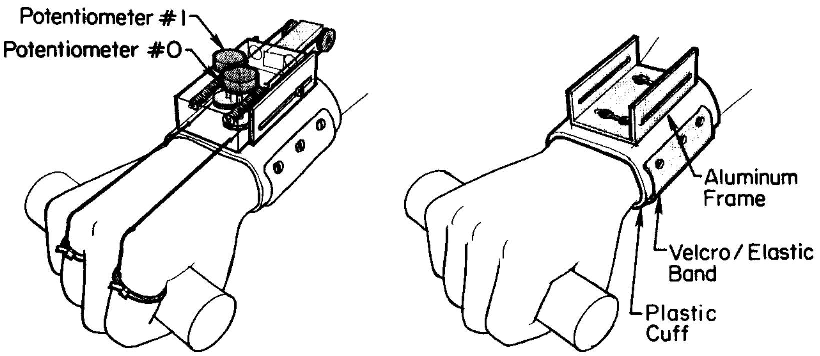


Figure 3. *Monitor used to collect wrist motion data.*

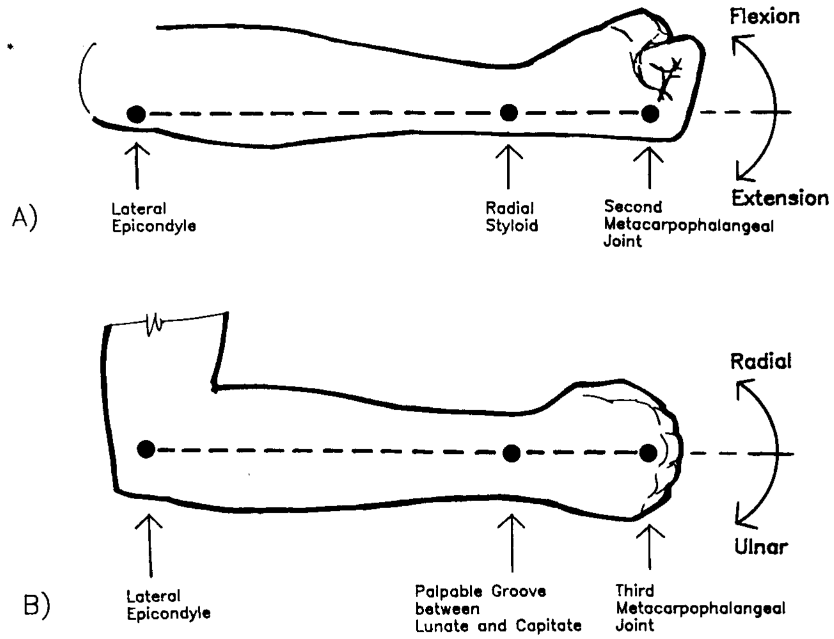


Figure 4. *Bony landmarks on the hand, wrist, and elbow that were used as reference points to align the wrist in a neutral position in the (A) flexion/extension plane and (B) radial/ulnar plane.*

were recorded by a video camera and later converted into force (newtons). The driving force of each strike was defined as the magnitude of the resultant force and was calculated by Equation 1 (Marras and Rockwell, 1986):

$$F = (Fx^2 + Fy^2 + Fz^2)^{0.5} \tag{1}$$

where F = resultant driving force and Fi = component force in the i direction.

For each hammering condition, the mean driving force was computed from all the strikes in that condition, which usually numbered 160 strikes per 3-min condition.

Accuracy. The accuracy of each strike was defined as the percentage of driving force that was delivered directly into the spike along the z axis. Accuracy was defined by Equation 2 (Marras and Rockwell, 1986):

$$\text{Accuracy} = Fz/[(Fx^2 + Fy^2 + Fz^2)^{0.5}] \tag{2}$$

For each hammering condition, the mean accuracy was computed for all strikes within that condition.

Number of misses. The number of times the subject's hammer missed the spike was counted in each condition.

Wrist angle. As illustrated in Figure 6, the voltage data from the wrist monitor were monitored by an ISAAC 2000 data acquisition system. The voltage data were collected at 50 Hz and were stored on an IBM AT. In subsequent analysis wrist angles were computed from regression equations that were calculated from the calibration data. Customized software pinpointed the windup and impact wrist angles of each strike in the radial/ulnar and flexion/extension planes. Means of the windup angles, impact angles, and range of motion were calculated for each condition.

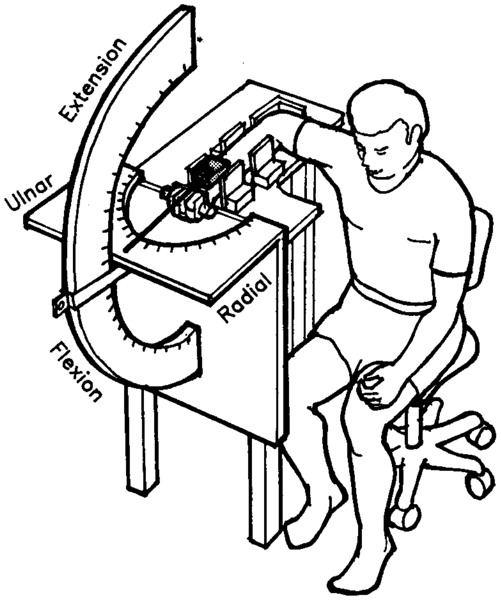


Figure 5. *Calibration table on which subject placed his hand and forearm in order to calibrate the wrist monitor.*

Statistical Analysis

The wrist angle data in both planes were considered collectively and were initially analyzed using a multivariate analysis of variance procedure (MANOVA). When results from MANOVAs were significant, follow-up analyses with individual ANOVAs were performed on all the wrist-angle dependent variables. All hammering performance data were analyzed with individual ANOVAs, and the source of the statistical significance was evaluated with post hoc procedures.

RESULTS

Wrist Angle

As illustrated in Figure 7, radial and ulnar wrist angles were measured as positive and negative angles relative to the forearm, respectively, and flexion and extension angles were measured as positive and negative angles, respectively.

Table 2 shows the significance levels of the MANOVA and ANOVA and Duncan's multiple comparison analyses. The MANOVA results reveal a significant angle and orientation effect but no interaction effect.

As shown in Table 2, all three hammer handle angles were significantly different from each other in ulnar deviation, yet there were no significant differences in radial/ulnar ROM. The straight hammer had the greatest ulnar deviation, whereas the 20- and 40-deg hammers had progressively less ulnar deviation. The straight hammer had the least radial deviation, and the 20- and 40-deg angled hammers had progressively more radial deviation. Thus there appears to be a trade-off between ulnar and radial deviation when bent handles are used. Figure 7 illustrates the radial and ulnar deviation and ROM of all three hammer angles. These results indicate that for all hammer handle angles the wrist started and ended at different angles in the radial/ulnar plane but spanned approximately the same number of degrees.

Figure 8a compares the starting and ending wrist angles during a hammering stroke for all three hammers. The starting and ending points of the three oblique lines are the mean wrist angles at windup and impact. The wrist starts at windup in an extended and radially deviated angle and moves obliquely to a flexed and ulnarly deviated angle at impact.

For the two hammering orientations, the only wrist angle that differed significantly was flexion at time of impact. As shown in Figure 9, wall hammering increased the ending flexion angle by 13.4 deg.

Driving Force

Table 3 indicates that the orientation effect was the only significant effect for driving force. In the wall orientation it averaged 24.17 kN—33.5% less average driving force

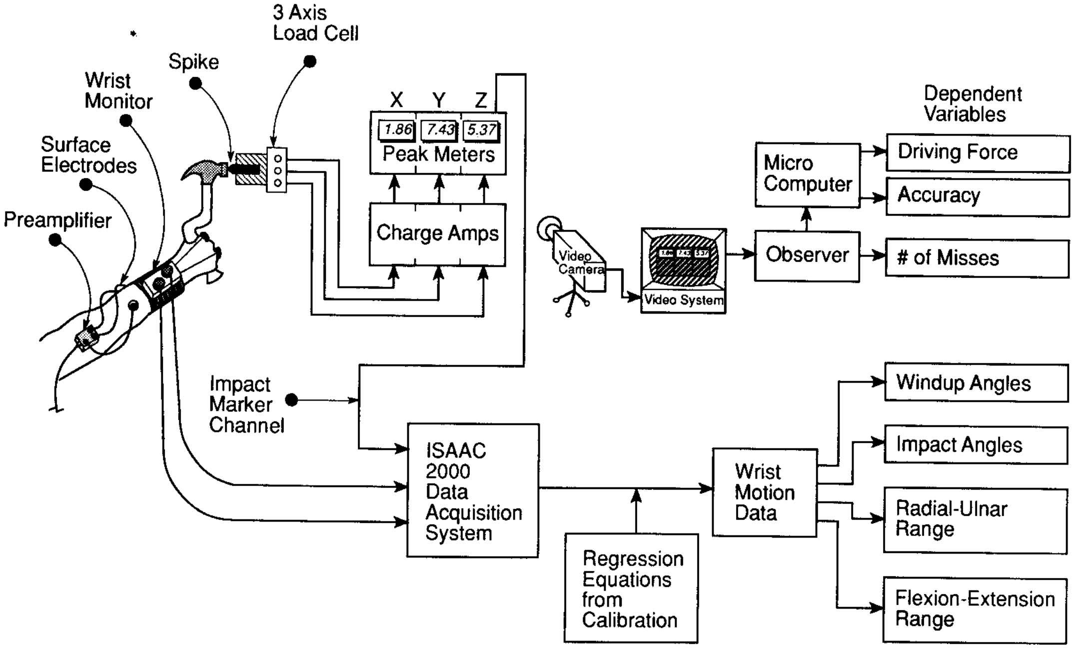


Figure 6. *Flow chart of how data were collected, conditioned, and analyzed.*

than in the bench orientation (36.35 kN). A nonsignificant spread in driving forces among all three hammer handle angles was observed, ranging from 30.64 kN (20 deg) to 31.01 kN (40 deg).

Accuracy

The handle angle effect for accuracy was not significant, as indicated in Table 3. However, the orientation effect for accuracy was significant. Accuracy in the bench orientation was significantly higher than in the wall orientation.

The angle-orientation interaction was significant for accuracy, as shown in Table 3. Figure 10a illustrates this angle-orientation interaction. In the bench conditions the accuracy measures for the three hammer handle angles were closely clustered, but in the vertical conditions these measures were spread out, with the 20-deg handle angle having the greatest accuracy.

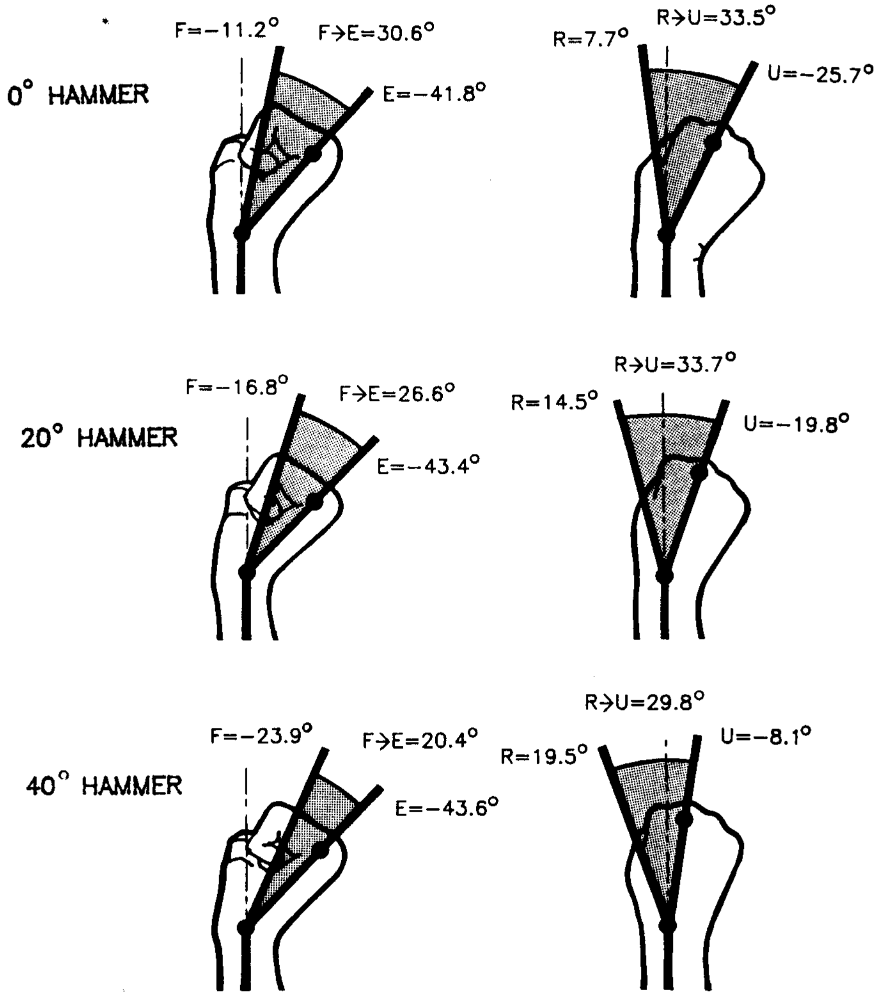
Number of Misses

The number of misses closely paralleled the accuracy patterns across angle and orientation. The number of misses in the wall condition averaged 28.58, about 350% higher than the 8.29 mean number of misses in the bench condition. Figure 10b illustrates the angle-orientation interaction for number of misses and shows that the 20-deg handle angle is associated with the fewest misses.

DISCUSSION

Biomechanics of Wrist

The mean wrist angles for the straight hammer agree well with the wrist angles reported in hammering studies that measured wrist angles with electrogoniometers (An, Askew, and Chao, 1986; Palmer, Werner, Murphy, and Glisson, 1985). Therefore, the wrist angle data collected from the 20- and



F = MEAN FLEXION ANGLE AT TIME OF IMPACT
E = MEAN EXTENSION ANGLE AT TIME OF WINDUP
R = MEAN RADIAL ANGLE AT TIME OF WINDUP
U = MEAN ULNAR ANGLE AT TIME OF IMPACT
F→E = MEAN RANGE OF MOTION IN FLEXION/EXTENSION PLANE
R→U = MEAN RANGE OF MOTION IN RADIAL/ULNAR PLANE

Figure 7. *Mean radial (R) and extension (E) wrist angles at windup, and mean ulnar (U) and flexion (F) wrist angles at impact as a function of hammer handle angle.*

40-deg hammer angles are probably representative of the population of novices.

As illustrated in Figure 7, the 20- and 40-deg hammers deviated approximately equally from the neutral position, with the 40-deg hammer having approximately the same amount of deviation radially that the 20-deg hammer had ulnarly. In this respect

TABLE 2

Levels of Multivariate and Univariate Significance and Duncan's Multiple Comparison Analysis of Wrist Motion Data

Dependent Variables	*Independent Variables*		
	Orientation	*Angle*	*Orientation × Angle*
MULTIVARIATE			
Wrist motion	$p = 0.0213^*$	$p = 0.0001^{***}$	$p = 0.9062$
UNIVARIATE			
Radial deviation (windup)	$p = 0.0906$	$p = 0.0103^*$ 0 20 40	$p = 0.9549$
Ulnar deviation (impact)	$p = 0.6066$	$p = 0.0001^{***}$ $\overline{40}\ \overline{20}\ \overline{0}$	$p = 0.4385$
Radial-ulnar range of motion	$p = 0.1201$	$p = 0.1439$	$p = 0.8295$
Flexion deviation (impact)	$p = 0.0003^{***}$ $\overline{\text{bench}}\ \overline{\text{wall}}$	$p = 0.0001^{***}$ $\overline{40}\ \overline{20}\ \overline{0}$	$p = 0.6337$
Extension deviation (windup)	$p = 0.7004$	$p = 0.5737$	$p = 0.9788$
Flexion-extension range of motion	$p = 0.0021^{**}$ $\overline{\text{bench}}\ \overline{\text{wall}}$	$p = 0.0004^{***}$ $\overline{40}\ \overline{20\ \ 0}$	$p = 0.2992$

* Significant at the 0.05 level; **significant at the 0.01 level; ***significant at the 0.001 level.
The lines under the significant independent variables illustrate which levels are significantly different from each other. Under each significant independent variable, the levels on the right are greater than the levels on the left.

the 20- and 40-deg hammers appear to follow good hand tool guidelines (Armstrong, 1983; Greenberg and Chaffin, 1977; Tichauer, 1978) in that they decrease the amount of ulnar deviation and maintain the wrist around the neutral position more than does the straight hammer. The 20- and 40-deg hammers should produce lower interstructural forces in the carpal tunnel, less tendon friction, and better-separated tendons because the wrist will be more neutrally aligned than with the straight hammer (based on Tichauer's principles, 1978).

The rates of CTD injury to the wrist caused by the hammer (Ohio Industrial Commission, 1984–1986) could possibly be reduced if the 20- and 40-deg hammers are used. However, wrist CTDs are generally underreported (Armstrong, 1983; Marras and Lavender, 1988), so the 5.0%–12.5% estimates of wrist CTDs caused by hammers are probably low. Consequently, the beneficial effects of the 20- and 40-deg hammers could potentially be much greater than what is suggested by the epidemiological data. However, a study of professional carpenters is needed in order to determine if angled hammers could reduce the injury rate of CTDs

Even though the radial and ulnar angles varied significantly across handle angles, the radial/ulnar ROM did not significantly change, as shown in Figure 7. The wrist was snapped approximately 32 deg in the radial/ulnar plane for all handle angles. The constant ROM for all three handle angles could possibly be explained in terms of dynamics

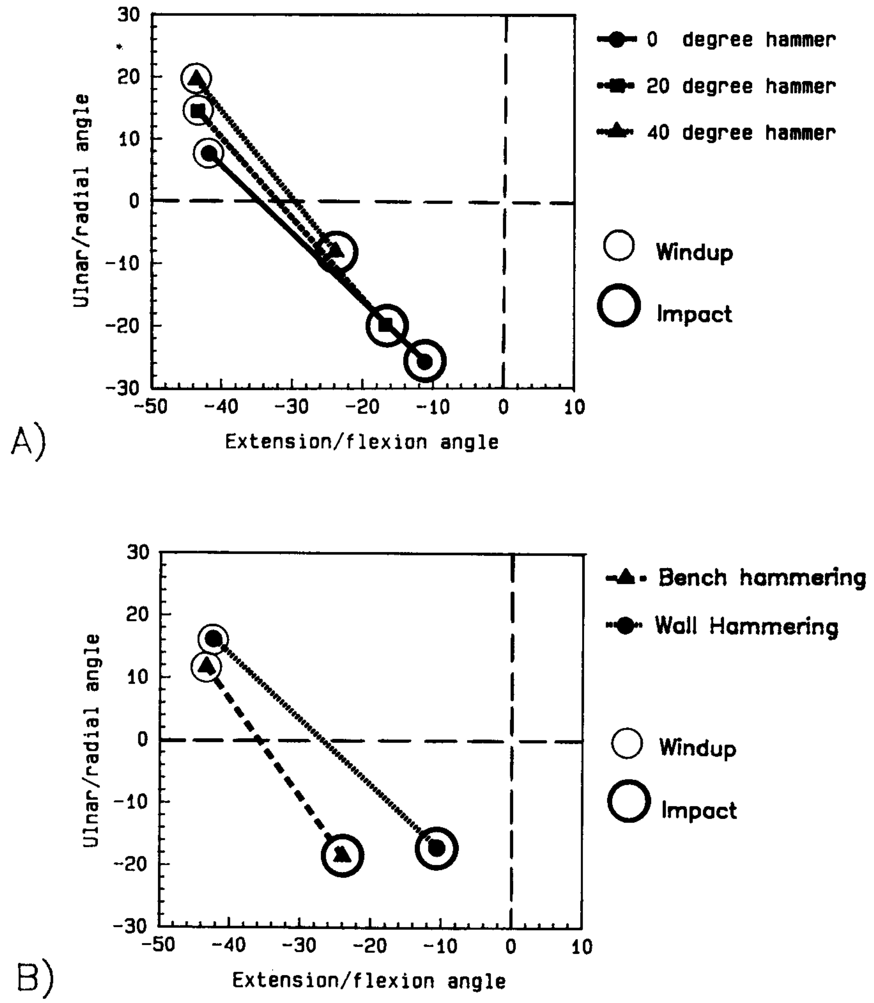


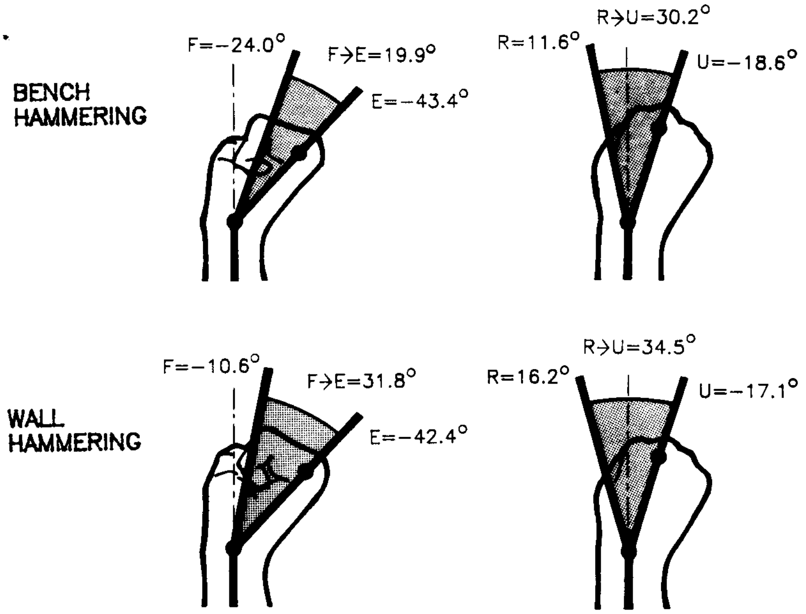
Figure 8. *Mean starting and ending angles of wrist motion during a hammering stroke from windup to impact as a function of (A) hammer handle angle and (B) hammering orientation.*

principles. The kinetic energy of the hammer has two components, translational and rotational, and the kinetic energy is defined in Equation 3:

$$\text{Kinetic energy of hammer} = \underset{\text{(translational)}}{0.5 \times M \times V^2} + \underset{\text{(rotational)}}{0.5 \times I \times W^2} \qquad (3)$$

where M = hammer mass, V = absolute velocity of hammer (m/s), I = hammer moment of inertia (kg × m^2), and W = absolute angular velocity of hammer (rad/s).

W, the hammer's absolute angular velocity, is the result of the rotation of the hammer from the shoulder, elbow, and hand. If the wrist were not snapped during a hammer stroke, then W would decrease because there



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F→E = MEAN RANGE OF MOTION IN FLEXION/EXTENSION PLANE
R→U = MEAN RANGE OF MOTION IN RADIAL/ULNAR PLANE

Figure 9. *Mean wrist angles at windup and impact as a function of hammering orientation.*

TABLE 3

Levels of Univariate Significance and Duncan's Multiple Comparison Analysis of Force, Accuracy, and Number of Misses

	Independent Variables		
Dependent Variables	*Orientation*	*Angle*	*Orientation × Angle*
UNIVARIATE			
Driving force	p = 0.0010*** wall bench	p = 0.8345	p = 0.5843
Accuracy	p = 0.0153* wall bench	p = 0.0649	p = 0.0410*
Number of misses	p = 0.0053** bench wall	p = 0.0622	p = 0.0427*

* Significant at the 0.05 level; **significant at the 0.01 level; ***significant at the 0.001 level.

The lines under the significant independent variables illustrate which levels are significantly different from each other. Under each significant independent variable, the levels on the right are greater than the levels on the left.

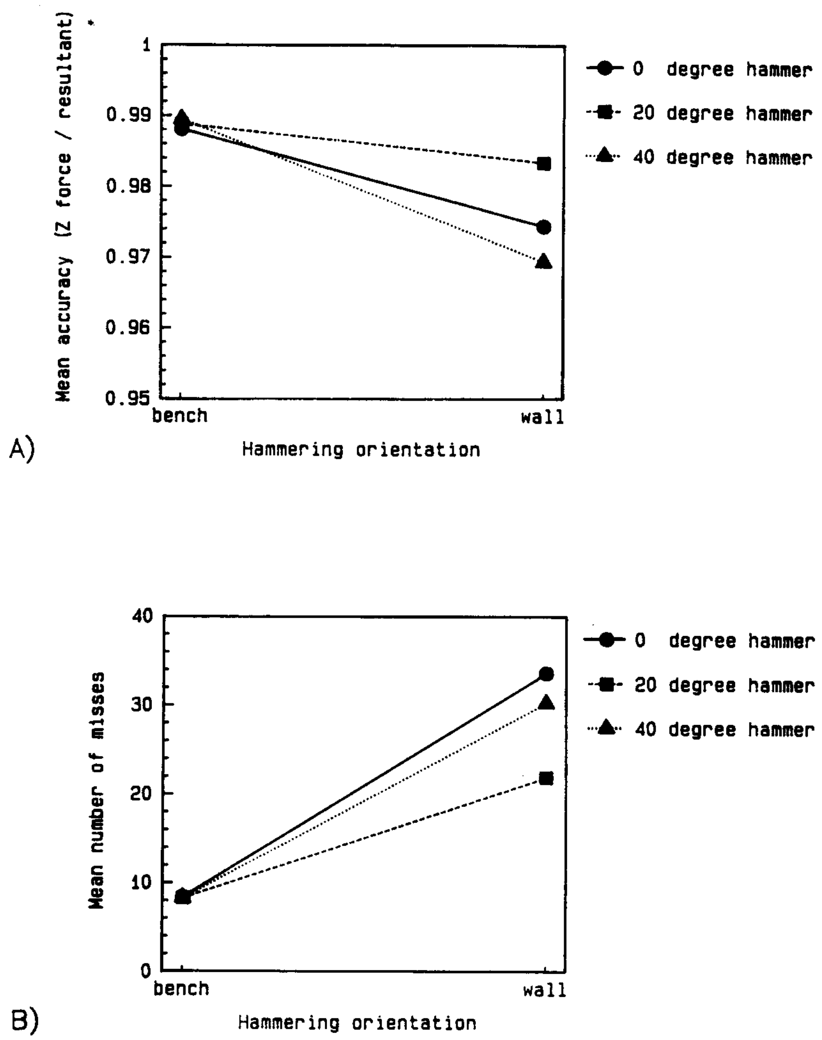

Figure 10. *Illustration of handle angle-work orientation interaction on (A) accuracy and (B) number of misses.*

would be no additional angular velocity from wrist rotation. It appears from Equation 3 that wrist snapping increases the total kinetic energy in the hammer over that obtained by hammering with a rigid wrist, which might be one reason subjects snap their wrists in hammering. The subjects might also have snapped their wrists approximately 32 deg because wrist snapping is a learned habit for force production.

Further calculations of force and energy of individual hammer strokes are necessary to explore the mechanical benefits of wrist snapping and why subjects snap their wrists. We are currently investigating the wrist motion components of wrist snapping, such as velocity and acceleration, and how these contribute to force generation.

Hammering orientation appeared to have a minimal effect on wrist angle, resulting in significant differences only in flexion angle at impact. Considering that there were no significant differences in radial and ulnar deviation between the two orientations, hammering orientation would probably not affect the incidence of hand/wrist CTDs arising from excessive ulnar deviation. However, there are performance trade-offs in vertical hammering that must be considered. Because less force and accuracy are generated in the wall orientation, more hammering strokes are required than in the bench orientation to produce the same amount of work. The increased number of wrist-snapping repetitions could increase the risk of hand/wrist CTDs.

As illustrated in Figures 8a and 8b, the mean starting and ending angles of wrist motion throughout a hammering stroke followed a dart thrower's movement. The oblique pattern of wrist movement is the natural functional pattern of wrist movement (Caillet, 1984; Capenar, 1956). The wrist moves obliquely because of the lines of action of the extensor carpi radialis (ECR) and flexor carpi ulnaris (FCU). The ECR retracts the wrist toward a radial and extended posture during the windup phase, whereas the FCU snaps the wrist toward an ulnar and flexed posture at impact.

Hammering Performance

The effect of hammer handle angle on performance in this study generally agreed with findings in the limited amount of research done on driving force and accuracy of angled hammers (Knowlton and Gilbert, 1983; Konz, 1986; Konz and Streets, 1984).

The decrease in driving force in the wall orientation can be attributed to the effects of gravity. The decrease in accuracy and threefold increase in number of misses in the wall orientation can probably be attributed to shoulder fatigue. In wall conditions the subject has to exert force in the shoulder muscles to elevate the arm and hammer. The shoulder muscles play a major role in stabilizing the arm. As these muscles become fatigued in the wall orientation, the arm becomes unstable and has diminished control during hammering strokes.

The detrimental effects of elevated arm posture on shoulder fatigue have been documented in the literature. Chaffin and Andersson (1984) showed that as shoulder abduction angle increased, the average time before subjects experienced severe pain decreased. Hagberg (1981) measured the fatigue of various shoulder muscles and found that fatigue started to develop within 1 min of arm elevation in the supraspinatus muscle and upper part of the trapezius muscle. Because of the elevated arm posture, wall hammering could have a substantial effect on the prevalence of shoulder CTDs.

Accuracy in the wall orientation tends to discriminate among the three hammer handle angles (see Figure 10a). Perhaps the 20-deg bent hammer is the most accurate in adverse hammering conditions, such as hammering upward or sideways, but does not perform any better than the other hammer handle angles in easy hammering conditions, such as bench hammering. However, the use of a 20-deg bent hammer might decrease the number of repetitions during a hammering bout and might therefore reduce the risk of injury.

CONCLUSIONS

Applying the established ergonomic principle of bending the tool and not the wrist to the hammer could produce less biomechanical stress on the wrist while maintaining the performance of a straight hammer. For novices, bending the hammer handle to 20 or 40 deg significantly reduces ulnar deviation and might decrease the incidence of CTDs caused by the hammer.

Changes in tool design (i.e., hammer angle) should not be studied independently of the task. This research clearly shows that the nature of the task (i.e., hammering orientation) significantly affects performance. Wall hammering severely decreases driving force and accuracy. Although wall hammering had little effect on wrist motion, it could have substantial effect on the prevalence of shoulder CTDs.

For a discussion of how hammer handle angle and work orientation affect forearm muscle fatigue, please refer to the companion article in this issue (Schoenmarklin and Marras, 1989).

REFERENCES

An, K. N., Askew, L. J., and Chao, E. Y. (1986). Biomechanics and functional assessment of upper extremities. In *Trends in ergonomics/human factors III* (pp. 573–580). Amsterdam: Elsevier.

Armstrong, T. J. (1983). An ergonomics guide to carpal tunnel syndrome. In *Ergonomics guides.* Akron, OH: American Industrial Hygiene Association.

Armstrong, T. J., Foulke, J. A., Joseph, B. S., and Goldstein, S. A. (1982). Investigation of cumulative trauma disorders in a poultry processing plant. *American Industrial Hygiene Association Journal, 43*(2), 103–116.

Caillet, R. (1984). *Hand pain and impairment.* Philadelphia: F. A. Davis Co.

Capenar, N. (1956). The hand in surgery. *Journal of Bone and Joint Surgery, 3B*(1), 128–151.

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

Damon, F. (1965). The use of biomechanics in manufacturing operations. *The Western Electric Engineer,* 9(4), 11–19.

Greenberg, L., and Chaffin, D. B. (1977). *Workers and their tools.* Midland, MI: Pendell Publishing.

Hagberg, M. (1981). Electromyographic signs of shoulder muscular fatigue in two elevated arm postures. *American Journal of Physical Medicine, 60*(3), 111–121.

Knowlton, R. G., and Gilbert, J. C. (1983). Ulnar deviation and short-term strength reductions as affected by a curve-handled ripping hammer and a conventional claw hammer. *Ergonomics, 26*(2), 173–179.

Konz, S. (1986). Bent hammer handles. *Human Factors, 28,* 317–323.

Konz, S., and Streets, B. (1984). Bent hammer handles: Performance and preference. In *Proceedings of the Human Factors Society 28th Annual Meeting* (pp. 438–440). Santa Monica, CA: Human Factors Society.

Marras, W. S., and Lavender, S. A. (1988). *Analysis of hand tool injuries in the underground mine industry* (Final Report, Contract No. J0348043). Pittsburgh, PA: U.S. Bureau of Mines.

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.

Meagher, S. W. (1986). Handtools: Cumulative trauma disorders caused by improper use of design elements. In *Trends in ergonomics/human factors III* (pp. 581–587). Amsterdam: Elsevier.

Ohio Industrial Commission. (1984–1986). *Injuries to carpenters/woodworkers caused by hammer.* (Available from the Research and Statistics Section, Division of Safety and Hygiene, Ohio Industrial Commission, Columbus, OH.)

Ohio Industrial Commission. (1985). *Carpenter (census occupational code 567) 1985 injury/illness statistics.* (Available from the Research and Statistics Section, Division of Safety and Hygiene, Ohio Industrial Commission, Columbus, OH.)

Ohio Industrial Commission. (1986). *Carpenters (census occupation code 567) 1986 injury/illness statistics.* (Available from the Research and Statistics Section, Division of Safety and Hygiene, Ohio Industrial Commission, Columbus, OH.)

Palmer, A. K., Werner, F. W., Murphy, D. M., and Glisson, R. G. (1985). Functional wrist motion: A biomechanical study. *Journal of Hand Surgery, 10A*(1), 39–46.

Schoenmarklin, R. W., and Marras, W. S. (1987). Measurement of hand and wrist position by a wrist monitor. In *Proceedings of the IX International Conference on Production Research* (pp. 410–416). Amsterdam: Elsevier.

Schoenmarklin, R. W., and Marras, W. S. (1989). Effects of handle angle and work orientation in hammering: II. Muscle fatigue and subjective ratings of body discomfort. *Human Factors, 31,* 413–420.

Tichauer, E. R. (1978). *The biomechanical basis of ergonomics: Anatomy applied to the design of work stations.* New York: Wiley.