



## Proximal forearm extensor muscle strain is reduced when driving nails using a shock-controlled hammer



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### ABSTRACT

**Background:** Repetitive hammer use has been associated with strain and musculoskeletal injuries. This study investigated if using a shock-control hammer reduces forearm muscle strain by observing adverse physiological responses (i.e. inflammation and localized edema) after use.

**Methods:** Three matched framing hammers were studied, including a wood-handle, steel-handle, and shock-control hammer. Fifty volunteers were randomly assigned to use one of these hammers at a fatiguing pace of one strike every second, to seat 20 nails in a wood beam. Magnetic resonance imaging was used to scan the forearm muscles for inflammation before the task, immediately after hammering, and one to two days after. Electromyogram signals were measured to estimate grip exertions and localized muscle fatigue. High-speed video was used to calculate the energy of nail strikes.

**Findings:** While estimated grip force was similar across the three hammers, the shock-control hammer had 40% greater kinetic energy upon impact and markedly less proximal extensor muscle edema than the wood-handle and steel-handle hammers, immediately after use ( $p < .05$ ).

**Interpretation:** Less edema observed for the shock-control hammer suggests that isolating handle shock can mitigate strain in proximal forearm extensor muscles.

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### 1. Introduction

Upper arm musculoskeletal disorders, such as lateral elbow tendinopathy, lateral epicondylitis, or “tennis elbow” are associated with strenuous tasks and manual work (Descatha et al., 2015), and were the subject of several recent prospective epidemiological studies (Fan et al., 2014; Herquelot et al., 2013; Descatha et al., 2013). Proximal elbow musculoskeletal injuries have been related to hammering (Geoffroy et al., 1994; Stasinopoulos and Johnson, 2006) and were observed in metal workers that hammered 8.4 h daily (Gangopadhyay et al., 2007).

Previous study of hammers from a biomechanical standpoint (Drillis et al., 1963) demonstrated that striking efficiency depended on the location of the hammer center of gravity and its radius of gyration. The principle of ‘bend the tool and not the wrist’ was tested and found that using a bent hammer handle marginally reduced ulnar deviation, muscle fatigue, and subjective discomfort (Schoenmarklin and Marras, 1989a, 1989b). Karwowski et al. (2003) observed that weight and grip softness

did not affect the number of nails hammered straight, while subjects identified handle design, weight, and hammer mass distribution as critical factors affecting their performance. Côté et al. (2005) found that repetitive hammering while fatigued affected motions of the wrist and elbow, suggesting adaptive strategies for sustaining productive work may increase the risk of injury to the neck and shoulders.

There is considerable indirect evidence that the shock loading in the hands from hammers could plausibly affect the risk of injury (Blackwell and Cole, 1994). Radwin et al. (1989) demonstrated that impulsive loading from power hand tools at different intensities affected forearm muscle responses. Delayed-onset muscle soreness and edema are often experienced following intense eccentric exercise (Shellock et al., 1991; Foley et al., 1999). The mechanism of edema is not well understood, but is associated with increased permeability of the blood vessels in response to inflammation following muscle damage, and is a potential precursor to the development of musculoskeletal injury. Signs of edema may be indicative of strain affecting involved anatomical regions.

Although hammering has been previously studied, no research has rigorously investigated use of shock-control hammer handles. Henning et al. (1992) considered forces generated by the impact between the tennis racket and ball and vibration transferred to the arm, to investigate how racket characteristics transmitted vibration to the forearm in tennis elbow.

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The central theory of the current study is that impulsive shock while hammering leads to inflammatory physiological responses. Prolonged exposure to muscle strain may indicate increased risk of injury. It has been shown that reduction of impulsive mechanical loading helped reduce the edema or inflammatory response, and provided noticeable differences in MRI signal intensity (Sesto et al., 2004; Sesto et al., 2005; Sesto et al., 2008). Chourasia et al. (2009) reported reductions in forearm stiffness and increases in edema up to 72 h after using a simulated power hand tool with rapid reaction forces, compared to slow reaction forces, and concluded that it could be explained by possible mechanical damage to muscle. It is therefore hypothesized that reduction in mechanical shock transmission to the hands will help decrease loading of the forearm muscles and signs of focal muscle edema, indicating reduced strain and potential insult to anatomical structures involved in lateral elbow injuries.

## 2. Methods

### 2.1. Participants

Fifty volunteers (Table 1) were recruited from the university community and consented to participate under IRB approval. Inclusion criteria included the ability to hammer for an extended period of time and lie still for an MRI. Participants were screened and excluded for self-reported previous surgeries, existing diseases, implanted devices, metal or metal fragments in the body, any physical or mental disabilities, and any other condition of which the researcher should be aware before interacting with the scanner.

Experienced participants self-identified having 20 h or more of cumulative hammering or carpentry work through employment, school, or hobby activities. All others were classified as inexperienced. There were 35 inexperienced and 15 experienced volunteers.

The participants were randomly assigned to one of the three different types of hammers, and used it to complete a fatiguing hammering task. No subject used more than one hammer in order to prevent carry-over effects from one condition to another.

### 2.2. Materials

The three framing hammers were similarly configured in size and weight, having different handle and head designs. The hammers (Fig. 1) were an Estwing, Rockford, IL (MRW20S) steel head, hickory wood handle hammer (WH), an Estwing, Rockford, IL (E3-20SM) steel head, steel handle hammer (SH), and a Fiskars, Madison, WI (IsoCore Framing) shock-control hammer (SC). All hammers had 0.57 kg heads and were similar in function. Of several different design features, the SC hammer contained an elastomeric sleeve located between the head and handle that allows a very small amount of movement, designed to attenuate shock transmission to the handle, when the hammer strikes.

### 2.3. Experimental task

The task which was intended to be fatiguing, consisted of repetitive hammering twenty 7.62-cm long 3D common nails. The nails were preset 3.81 cm deep in an 81.28-cm long piece of 10.16 by 10.16 cm Douglas Fir wood. The plank was attached to a height adjustable platform on a horizontal surface and set for a 90° included elbow angle when the hammer head first strikes. A metronome sounding at 120 beats/min was used to control the pace at one strike every second



Fig. 1. The three hammers analyzed for the study: (1) Wood “WH”, (2) Steel “SH”, (3) Shock Control “SC”. Their respective center of masses and grip locations are labeled.

by instructing the participant to strike a nail on every other beat. All participants wore eye and hearing protection while hammering.

Participants completed a discomfort survey after completing the hammering task, rated on a scale from 0 to 10 (0 = no discomfort, 10 = maximum discomfort). Only upper limb discomfort for the hammering hand was considered, including the shoulder through the hand. The maximum discomfort reported was used for analysis.

### 2.4. Energy of strike

High-speed video was used to measure the mean impact velocity and to calculate kinetic energy ( $KE$ ) and power of impact ( $P$ ). A Nikon 1 V2 camera equipped with a 1 NIKKOR 18.5 lens captured 400 frames/s high-speed video for approximately 3 strikes during the participants' second nail. The head of the hammer was tracked from the down stroke through the impact with the nail, as seen in Fig. 2.

Custom marker-less tracking software (Chen et al., 2014) measured the velocity in pixels/s, which was then converted into meters/s by using the frame rate and a known distance in the image. The velocity was used in equations from Drillis et al. (1963) to find the  $KE$  and  $P$ .

The  $KE$  of a strike (Eq. (1)) considered the mass of the hammer,  $m_h$ , the striking velocity,  $v_s$ , the hammer inertia,  $I_h$ , and the angular velocity,  $\omega_s$ . The mass of the hammer,  $m_h$ , striking velocity,  $v_s$ , striking acceleration,  $a_s$ , the hammer inertia,  $I_h$ , the angular velocity,  $\omega_s$ , angular acceleration  $\alpha_s$ , gravitational acceleration,  $g$ , and the projection of the acceleration due to gravity in the direction  $\beta$  of the striking velocity,  $\cos(\beta)$ , were used to calculate the final  $P$  of the strike in Eq. (2).

$$KE = \frac{m_h v_s^2}{2} + \frac{I_h \omega_s^2}{2} \quad (1)$$

$$P = m_h v_s a_s + I_h \omega_s \alpha_s + m_h v_s g \cos(\beta) \quad (2)$$

The hammer moments of inertia about its center of were measured by suspending each tool and using the oscillation method (Table 2). The parallel axis theorem was applied to determine the mass moment of inertia for calculated arm length based on each participant's stature using the NASA (1978) segment stick figure model.

Table 1  
Participant demographics grouped by hammer.

Hammer type	Number of participants	Male/female	Number of experienced	Mean age (yr)	Mean stature (cm)	Mean body weight (kg)
Wood handle (WH)	16	10/6	5	23.63	170.51	68.75
Steel handle (SH)	18	11/7	5	22.11	172.01	67.44
Shock control (SC)	16	11/5	5	22.56	172.87	70.17

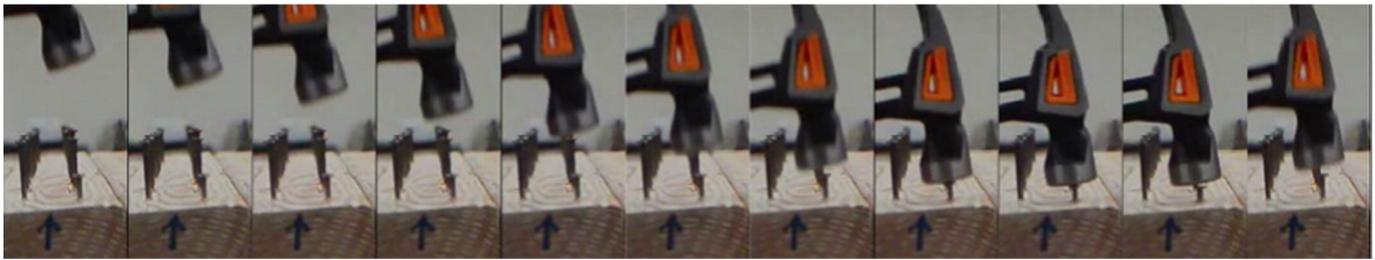


Fig. 2. Sequence of frames capturing the hammer head impact with the nail. Time progresses 0.005 s in each frame.

### 2.5. Grip force estimates during hammering

Grip force was estimated from forearm electromyogram (EMG) signals collected during the hammering task using an EMG calibration procedure. An electronic hand dynamometer fitted with a 3.81 cm diameter cylindrical handle was used to obtain grip force (Radwin et al., 1991). To mimic posture during hammer strike, participants stood upright holding their forearm and dynamometer parallel to the ground while the upper arm created a 90° elbow angle, similar to holding a hammer, and gripped a maximum voluntary contraction (MVC) for 8 s.

The EMG data acquisition system included a 16-channel EMG transmitter unit (TeleMyo model 2400T G2, Noraxon Inc.), four EMG active leads with one ground lead, CF Wi-Fi radio card, PCMCIA receiver card (Cisco Aironet 802.11a/b/g wireless card bus adapter, Cisco Systems, Inc.), and a data collection laptop computer. MyoResearch XP software was used to record EMG activity. EMG recordings were captured before, during and after hammering for a 3000 Hz sampling rate using a 5 Hz to 500 Hz Butterworth band pass filter.

Pairs of 1 cm Ag/AgCl EMG electrodes were affixed over the extensor carpi radialis and flexor carpi radialis on the hammering forearm using a strong tack adhesive. Leads were placed with the ground electrode on the lateral bony prominence of the elbow.

The corresponding grip force was calibrated for a given participant by holding the grip dynamometer in a position similar to the strength test, described above. A moving root-mean-square (RMS) of the EMG with a window of 850 samples was calculated, and a calibration EMG level was obtained for each participant using the mean amplitude of the RMS flexor EMG signal recorded over the middle 5 s of an 8 s controlled exertion, randomly set to 25%, 75%, and 50% MVC. This EMG during the hammering task was compared against a linear regression of the dynamometer force level and the calibration RMS EMG in order to estimate grip force.

The grip force was measured while hammering nails 2 through 4. Nail 1 was excluded to allow participants to become fully accustomed to the task. The flexor signal corresponding to 100 ms before impact was considered indicative of the participant's grip force while swinging the hammer prior to contact with the nail in order to minimize motion artifacts from impact. The average flexor EMG values at 100 ms before extensor minima were calculated and converted to grip forces (Fig. 3). The electrode signal was monitored for signs of motion artifacts and tested for integrity prior to and after hammering.

Additional EMG data was collected for a 50% MVC grip immediately after completing the task and were analyzed to verify that participants were fatigued. A decrease in the mean power frequency (MPF) and increase in mean amplitude were indicative of muscle fatigue. EMG data

for two participants were excluded due to electrode failure from hammering.

### 2.6. Magnetic resonance imaging

Magnetic resonance imaging (MRI) was used to evaluate short-term effects of localized edema in anatomical structures associated with lateral epicondylitis, including the extensor carpi radialis brevis, extensor carpi radialis longus, and extensor digitorum communis muscles. Each participant had their hammering arm imaged just below the elbow while supinated: (1) before, (2) immediately after (within 5–10 min), and (3) one to two days after hammering.

The MRI was a GE Healthcare Artoscan extremity scanner with a 0.17 T permanent magnet. The 2D acquisitions were performed with a fluid-sensitive short tau inversion recovery (STIR) sequence. The imaging parameters for the scan were a repetition time of 2050 ms, echo time of 26 ms, inversion time of 75 ms, field of view of 140 × 140 mm, matrix of 256 × 256 pixels, and slice thickness of 7 mm. The total scan time was 4 min, 30 s per scan.

The image processing software ImageJ was used to analyze the MR images for signs of edema by displaying a higher signal intensity than the surrounding tissues on the fluid sensitive STIR scans. An image was selected at the same anatomic location, approximately 2 cm below the elbow joint in each participant on each of the three scans performed before, immediately after, and one to two days after hammering. The analyst was blinded as to which hammer was used.

By visual inspection, two regions of interest (RoI) were defined in each of the three selected images using the freehand-selection tool. The first region was the high-intensity signal areas of edema, found in all participants after hammering in the proximal musculature of the posterior forearm. The brachioradialis muscle was used to normalize the signal intensity across scans, accounting for any potential variance due to recalibration between scans, due to its close proximity to the muscles of interest, therefore increasing the likelihood for being in a homogeneous magnetic field.

An intensity ratio was calculated using the ImageJ ratio analysis feature for each of the three scan times, and these ratios were used to analyze for differences in muscle edema before hammering, after hammering, and one to two days after hammering.

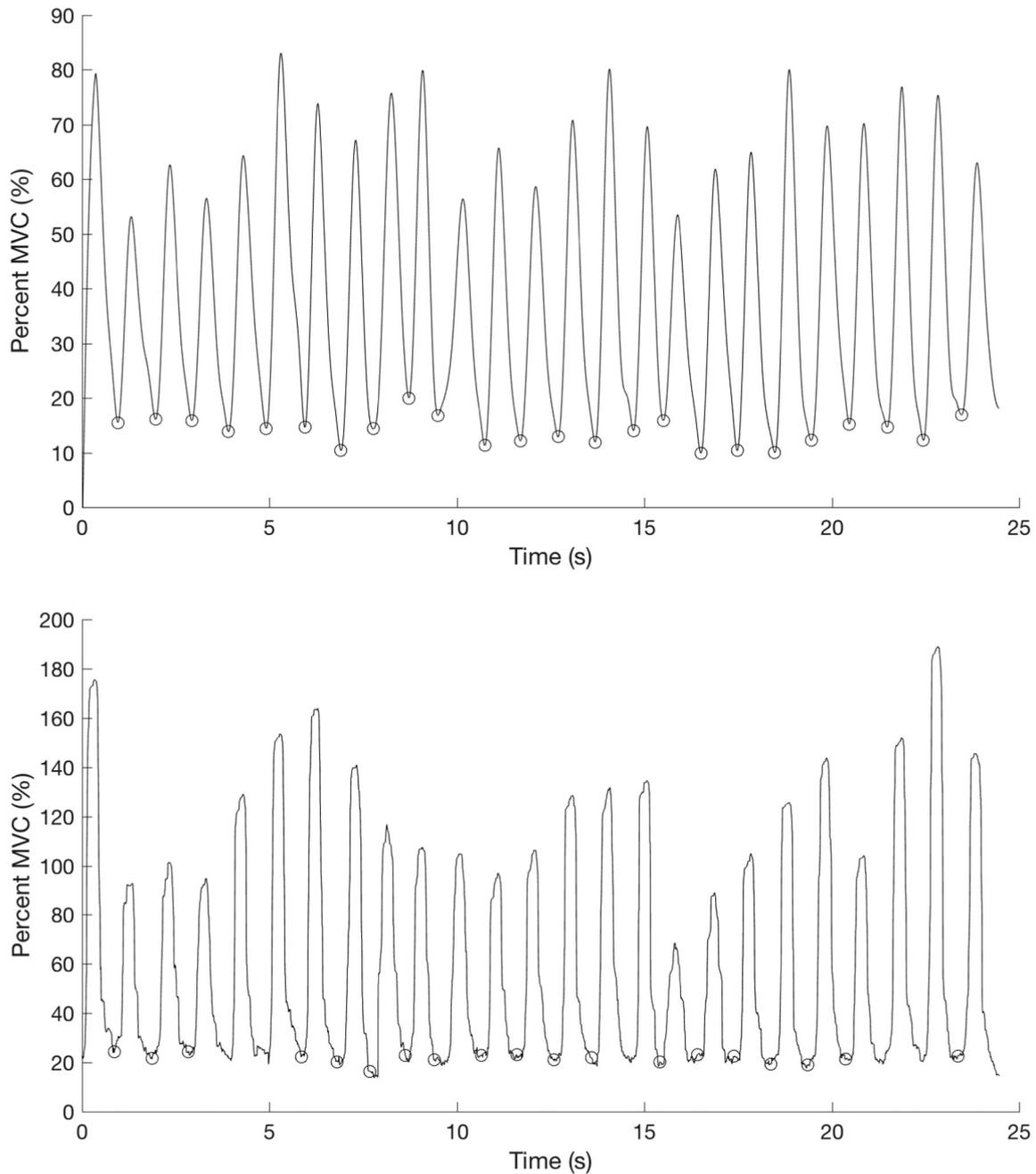
### 2.7. Experimental design and statistical analysis

The independent variables were hammers (WH, SH, and SC), time of scan (before, immediately after, and one to two days after hammering), and experience (experienced, inexperienced). Time was a repeated measures variable, since each participant had an EMG recording before and immediately after hammering, and an MRI all three times.

Due to the small number of experienced females (two) and because none were randomly assigned to the SC hammer, grip strength was used as a covariate to account for the effect of gender. For EMG MPF and RMS amplitude, and for the MRI contrast ratios, the factors were the hammer, experience level, and time of scan, and no covariates were included.

Table 2  
Hammer mass and moments of inertia.

Hammer	Mass (kg)	Inertia (kg m <sup>2</sup> )
WH	0.744	0.0388
SH	0.868	0.0375
SC	0.896	0.0482



**Fig. 3.** Top: Representative extensor EMG signal in terms of percent maximum voluntary contraction (MVC) for Nails 2–4 with local minima circled. Bottom: Corresponding flexor EMG signal with time of 100 ms before extensor minima circled.

The dependent variables were estimated grip force, KE, P, localized discomfort, and muscle edema in the proximal forearm. The results were all tested for statistical significance using analysis of variance. A Tukey's pairwise comparison tested the difference in intensities across different hammers at the same scan time, as well as the same hammer at different times. The results are reported, with significance levels set at 95%.

### 3. Results

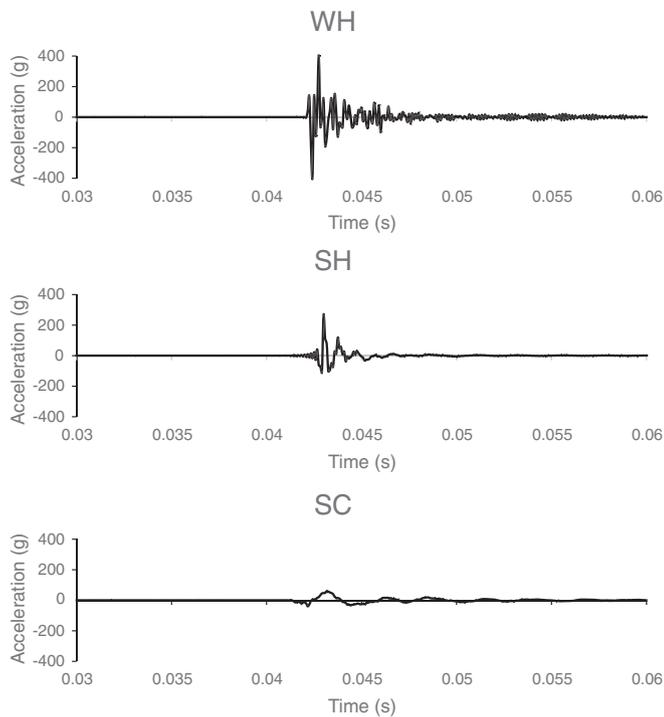
#### 3.1. Hammer shock characteristics

A time plot of the dominant z-axis acceleration (aligned perpendicular to the handle through the hammer strike face), measured from a tri-axial accelerometer affixed to each handle at the respective grip location

(ISO, 2001) is provided in Fig. 4 (Fiskars Brands Inc., 2016). The hammers were attached to a fixture designed to impart a controlled impulse to the striking face using a pendulum mechanism released from a set distance for creating a repeatable strike force. Each hammer was mounted in a clamp that allowed it to rotate about its center of mass when struck.

#### 3.2. Estimated grip force and energy of strike

No effect of grip force was observed among hammers ( $F(2,38) = 0.85, p = .45$ ), or experience ( $F(1,38) = 0.20, p = .66$ ), while using strength as a covariate ( $F(1,38) = 9.08, p = .005$ ). The mean grip force was 208.9 N (SD = 340.3) for the WH hammer, 216.9 N (SD = 370.8) for the SH hammer, and 201.5 N (SD = 177.0) for the SC hammer. The hammer  $\times$  experience interaction ( $F(2,38) = 4.74, p = .015$ ) was statistically significant, where experienced participants ( $N = 5$ )



**Fig. 4.** Representative shock acceleration time series plots for each hammer in the z-axis for the wood handle (WH), steel handle (SH) and shock-control (SC) hammers.

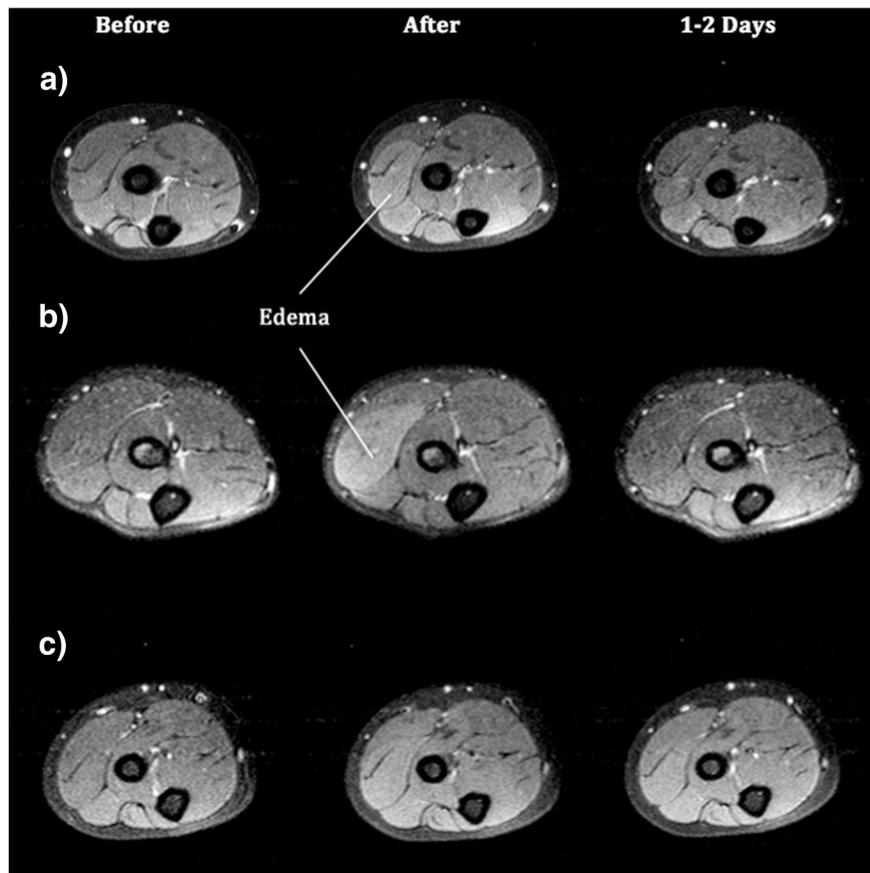
using the SH hammer exerted 570.0 N (SD = 595) while inexperienced participants (N = 13) exerted 80.9 N (SD = 68.8).

Initial impact velocity was greatest for the SC hammer ( $F(2,43) = 3.31, p = .05$ ). The mean initial velocity was 2.01 m/s (SD = 0.62) for the WH hammer, 1.87 m/s (SD = 0.74) for the SH hammer, and 2.20 m/s (SD = 0.75) for the SC hammer. No significant effects were observed for experience ( $F(2,43) = 2.56, p = .12$ ) or for the hammer  $\times$  experience interaction ( $F(2,43) = 2.08, p = .14$ ), while using grip strength as a covariate ( $F(1,43) = 12.11, p = .001$ ).

A significant difference was observed between the mean nail strike KE among hammers ( $F(2,43) = 4.45, p = .02$ ). The SC hammer KE (mean = 8.12 J, SD = 5.04) was 40% greater than the WH (mean = 5.82 J, SD = 3.24) and 39% greater than the SH hammer (mean = 5.83 J, SD = 5.44). No significant effect was observed for experience ( $F(1,43) = 3.09, p = .09$ ) or for the hammer  $\times$  experience interaction ( $F(2,43) = 2.31, p = .11$ ), while using grip strength as a covariate ( $F(1,43) = 11.8, p = .001$ ).

The mean initial P was 29.40 kg m<sup>2</sup>/s<sup>3</sup> (SD = 14.81) for the WH hammer, 24.69 kg m<sup>2</sup>/s<sup>3</sup> (SD = 15.29) for the SH hammer, and 38.22 kg m<sup>2</sup>/s<sup>3</sup> (SD = 24.33) for the SC hammer. The effect of hammer was marginally significant ( $F(2,43) = 3.01, p = .06$ ), while no significant effects were observed for experience ( $F(1,43) = 0.03, p = .86$ ) or for the hammer  $\times$  experience interaction ( $F(2,43) = 0.22, p = .80$ ), while using grip strength ( $F(1,43) = 9.54, p = .004$ ).

The effect of grip strength for gender was statistically significant ( $F(1,48) = 21.16, p = .000$ ). Average male grip strength was 416.1 N (SD = 146.7) while average female grip strength was 246.6 N (SD = 69.9).



**Fig. 5.** Example of MRI before hammering, after hammering, and 1–2 days later with either (a) WH, (b) SH, and (c) SC hammers. Edema due to hammering is observed via a higher intensity signal in the extensor muscles. Note that the brachioradialis muscle showed no increased signal intensity after hammering.

The average number of strikes measured for nails 2 through 4 was 15.65 for the WH, 20.3 for the SH and 17.4 for the SC hammers, and 20.98 for inexperienced and 12.85 for experienced participants. The average number of strikes was inversely related to strength ( $F(1,30) = 7.92$ ,  $p = .009$ ), however no statistically significant effects were observed for hammer ( $F(2,30) = 0.55$ ,  $p = .58$ ) or experience ( $F(1,30) = 2.87$ ,  $p = .10$ ).

### 3.3. Localized discomfort and fatigue

The mean discomfort was 4.19 (SD = 2.74) for the WH, 3.94 (SD = 2.90) for the SH, and 3.53 (SD = 2.80) for the SC hammer. No main effect for discomfort was observed among hammers ( $F(2,41) = 0.89$ ,  $p = .42$ ) however a significant but small interaction between hammer  $\times$  experience was observed ( $F(2,41) = 3.53$ ,  $p = .04$ ). The difference between experienced and inexperienced participants for the WH hammer was 4.19 ( $p = .03$ ) while no significant ( $p > .05$ ) differences between experienced and inexperienced participants were observed for the other hammers.

Differences in discomfort were observed when comparing inexperienced and experienced participants, averaged over all hammers ( $F(1,41) = 8.60$ ,  $p = .005$ ). Inexperienced participants reported greater mean discomfort of 4.73 (SD = 2.39) than the experienced participants that had discomfort of 2.07 (SD = 2.74). No grip strength effect was observed ( $F(1,41) = 2.28$ ,  $p = .14$ ).

In total, the hammering task fatigued all participants, as evidenced by the consistent decrease in EMG MPF shift and increase in mean amplitude. While using grip strength as a covariate ( $F(1,83) = 4.27$ ,  $p = .04$ ), average MPF decreased in frequency from 92.4 Hz (SD = 28.4) to 41.3 Hz (SD = 16.0) after hammering ( $F(1,47) = 137.28$ ,  $p = .0001$ ). No significant EMG frequency effects were observed for hammer ( $F(2,47) = 1.49$ ,  $p = .22$ ) or experience ( $F(1,47) = 0.13$ ,  $p = .87$ ). Similarly, an overall increase in mean amplitude was observed from 28.7  $\mu$ V (SD = 21.7) to 55.8  $\mu$ V (SD = 35.0) after hammering ( $F(1,47) = 92.41$ ,  $p = .0001$ ). No significant EMG amplitude effects were observed for grip strength ( $F(1,83) = 1.71$ ,  $p = .13$ ), hammer ( $F(2,83) = 0.57$ ,  $p = .56$ ) or experience ( $F(1,83) = 2.03$ ,  $p > .13$ ). No significant interactions were observed.

### 3.4. Physiological responses

The SC hammer had markedly less proximal extensor edema in the posterior musculature than the WH and SH hammers, immediately after use (Fig. 5). No increases in signal intensity were observed in the brachioradialis muscle.

The intensity ratios for each hammer over the three scan times are plotted in Fig. 6. A statistically significant difference between hammers ( $F(2,126) = 4.56$ ,  $p = .01$ ) and time ( $F(2,94) = 36.29$ ,  $p = .00$ ) was observed. No significant effects were observed for experience ( $F(1,126) = 1.33$ ,  $p = .18$ ), or any interactions between hammer, experience and time.

The Tukey pairwise post-hoc comparison test found that before hammering, the MRI intensity ratios for all hammers were similar ( $p > .05$ ), with an average intensity ratio of 1.21 (SD = 0.11). After hammering, the intensity ratio increased more for the WH and SH hammer than for the SC hammer. No statistically significant difference was observed ( $p > .05$ ) between the WH and SH hammers. The SC hammer average signal intensity was 11% less than the WH hammer ( $p = .04$ ) and 12% less than the SH hammer ( $p = .01$ ). After one to two days, the intensity ratios for all hammer groups had no statistically significant post-hoc differences ( $p > .05$ ).

## 4. Discussion

The WH and SH hammer groups markedly increased MRI signal intensity after hammering, indicating more edema, while the SC hammer

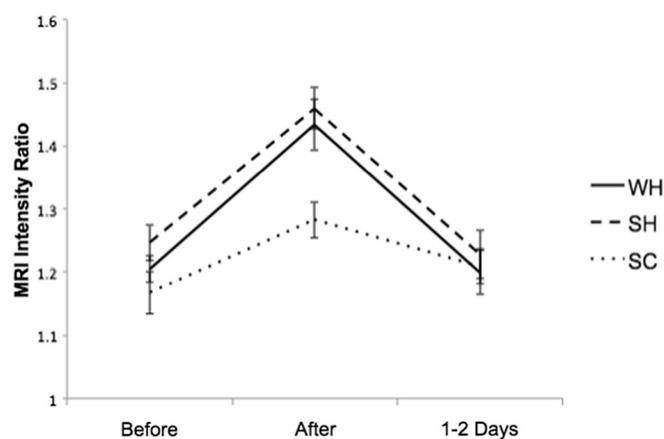


Fig. 6. Average MRI intensity ratio for before, after, and one to two days after use. Error bars are one standard deviation.

did not increase in average intensity after hammering. All hammer groups had a reduction in muscle edema comparable to their initial state within one to two days after the experiment, which was indicative of a short-term strain effect.

The smaller edema effect for the SC hammer might suggest a difference in the way the load is transmitted from the hands to the forearm extensor muscles. This is likely due to the shock-absorbing characteristics in the SC handle, which may isolate the impulse loading transmitted to the forearm. Edema was localized to the proximal extensors and no edema was observed in the brachioradialis muscle after hammering, suggesting that the effect was associated with specific exertions and not general vibration transmitted through the forearm to the proximal tissues.

It is not clear that the results are reflective of an injurious edematous response, as edema appeared to be resolved by the time of the 1–2-day follow-up MRI. There may have been a brief acute inflammatory response; however, the results may simply be indicative of increased blood flow in the region post-exercise (a normal response to exercise). Although edema was observed, we cannot necessarily conclude that the prolonged use of hammers would lead to long-term injuries. Further study that examines actual use in the field for an extended period of time would be necessary.

The SC hammer had the greatest KE upon impact, while the KE for the WH and SH hammers were both less. These results imply the SC hammer was more task-effective and delivered more energy to its target per strike. The outcome is a combination of hammer inertial characteristics (Table 2) and kinematics while driving nails. This finding is noteworthy when considering that the SC hammer delivered greater KE and P than the WH and SH hammers, yet resulted in less muscle edema. Grip force for the SC hammer was similar to the other hammers, so grip force cannot explain the differences in edema observed. Furthermore, no differences were observed in discomfort. As such, the SC hammer did not exhibit noticeable differences in discomfort when compared to the WH and SH hammers, although greater energy was imparted against the nails. Consequently, impulse loading in the handles was the major difference among the hammers.

Differences in edema responses were not observed among experienced and inexperienced participants, so there was no suggestion that experienced participants adapted, although this might be due to the particular criteria for experience. Blackwell and Cole (1994) reported wrist kinematic and EMG data for novice tennis players that showed they contracted their wrist extensor muscles throughout the stroke, and that contributed to stretch of wrist extensor muscles upon collision of the ball and racket.

The male grip strength SD appeared larger than typically observed for a random sample. This may have occurred because participants were recruited for a study that required use of hammers, which may

have attracted more physically fit participants than the general population. The coefficient of variation (SD/mean) was 0.35 for males and 0.28 for females, which was considered not too different. A Grubbs' outlier test on strength, stratified by gender, found no outliers at the 5% level of significance ( $p = 1.0$  for females and  $p = .065$  for males). Since no significant grip force differences were observed between the hammers, it is reasonable to conclude that grip force was not related to the increased edema observed for the WH and SH hammers.

This experiment had some additional noteworthy limitations. Participants could not experience all three hammers, as there were no repeated measures due to limitations on time and participant availability to return for three independent sessions after sufficient rest and recovery. Since the participants were divided across three hammer groups, the sample size for each hammer was still relatively small.

In addition, common practice in MRI for quantifying muscle edema is to measure T2 relaxation time of the tissue using a multi-echo T2 mapping sequence. However, this method would require the acquisition of multiple scans over an excessive period of time, which was not deemed practical with the low-field strength MRI scanner available for this study. Therefore, the signal intensity ratio was calculated instead.

Within in the context of tool design, the results indicate that the SC hammer actually increased hammering performance while reducing the inflammatory physiological response. The implications of these findings for practice in occupational injury prevention support utilization of SC hammers, particularly for jobs that involve extensive hammer use.

## 5. Conclusions

This study sought to determine whether the use of an SC hammer can reduce inflammation responses that might indicate an increased risk of forearm musculoskeletal injuries, such as lateral epicondylitis. Although there were no statistically significant differences in estimated grip force or perceived discomfort across the hammers, MRI analysis revealed a marked relationship between the type of hammer used and the level of edema in the proximal forearm wrist extensor muscles. The SC hammer had lower levels of edema than the WH or SH hammers. In terms of efficiency, the SC hammer delivered more energy to its target. Overall, this study showed promise that SC hammers may help prevent adverse musculoskeletal responses due to hammering.

## Acknowledgements

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