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The effect of handle characteristics of a hammer stapler on biomechanical and physiological response

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ABSTRACT

THE EFFECT OF HANDLE CHARACTERISTICS OF A HAMMER STAPLER ON BIOMECHANICAL AND PHYSIOLOGICAL RESPONSE

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Frequent and prolonged use of an improperly designed hand tool not only affects productivity but may also cause painful symptoms which, if left untreated, can develop into chronic musculoskeletal disorders (MSDs). This study was undertaken to assess the effects of ergonomic guidelines related to grip characteristics of a hammer stapler. Specifically, surface composition, shape, and angle of grip were investigated. Three commercially available hammer staplers were selected for this study. Tool #1 had a basic grip design, Tool #2 had a somewhat improved grip design, and Tool #3 incorporated most of the ergonomic design guidelines in terms of grip surface, grip shape, and grip angle. In a laboratory setting, 16 male participants used each of these tools on each of two simulated roof pitches at 4:12 and 6:12 inclines. Each experimental trial consisted of stapling roofing underlayment onto the simulated roof at a frequency of 1 staple per second for a two-minute duration. At a significance level of 5%, Tool #3 produced lower discomfort ratings in fingers and hand and higher favorable ratings for perceived grip comfort and protection from injury. Tool #3 also had significantly lower ($p<0.05$) muscle EMG in the flexor carpi ulnaris and lower ulnar deviation of the wrist angle at the instant of tool impact. The outcome of this study strongly favors implementation of ergonomic guidelines in hand tool design for non-powered, impact type hand tools. The quantitative results derived from this study would be useful in making design improvements in future hand tool design.

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by
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APPROVAL PAGE

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I dedicate this thesis to my father, Dr. Richard S. Latta, in recognition of his zealous encouragement, generous support, and powerful inspiration.

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CHAPTER 1

INTRODUCTION

1.1 Overview

Non-powered hand tools are widely used in the construction, manufacturing, and agricultural industries. Frequent and prolonged use of an improperly designed hand tool may cause injury to muscles, tendons, nerves, ligaments, joints, cartilage, spinal discs, or blood vessels. Common symptoms of such soft tissue injuries include tingling; swelling in the joints; decreased ability to move; decreased strength; pain from movement, pressure, or exposure to cold or vibration; continued muscle fatigue; sore muscles; numbness; and change in the skin color of hands or fingertips. Untreated, these symptoms can develop into chronic musculoskeletal disorders (MSDs) such as tendonitis, tenosynovitis, bursitis, epicondylitis (tennis elbow), carpal tunnel syndrome and de Quervain's syndrome. Musculoskeletal disorders are attributable to hand tool use in occupational settings and result in pain to the worker, lost workdays, and economic costs. Major work factors affecting health and performance of hand tool users include tissue compression, static load on arms and upper body muscles, awkward working positions / body postures, and vibration.

Prevention of MSDs is possible through proper design and selection of hand tools. Some manufacturers label their tools as "ergonomically designed". However, it is often difficult to evaluate hand tools from an ergonomic perspective. A tool becomes "Ergonomic" only when it fits the task being performed, and, it fits the worker's hand without causing awkward postures, harmful contact pressures or other safety and health risks. To this end, even though ergonomic guidelines have long been proposed in the textbooks, the design of many commercial tools continues to lack implementation of these guidelines. One of the reasons for such non-compliance to guidelines might come from a paucity of evidence-based studies evaluating the effectiveness of said guidelines.

Tool studies (Jung et al. 2005; Konz and Streets 1984; Roquelaure et al 2004; Strasser et al 1996) which evaluated different hand tool interface characteristics are often tool specific and do not encompass a broad range of hand tools. As a result, outcomes of those studies are not readily transferable to other tool types. The literature survey section of this thesis discusses the details of the relevant studies. One commonly used category of hand tool is one handed, non-powered impact type tool. This tool utilizes impact force generated by striking the tool on to a hard surface, an example being the hand operated hammer. For this category of hand tools, only one study (Konz and Streets 1984) evaluated hammer handles having different angles based on qualitative preferences and productivity measures. However, quantitative biomechanical and physiological effects on the users of the tool which may have closer relationships with the design related MSD risk factors are not available. Hammer staplers are commonly used by roofing installers to staple paper underlayment on plywood roof decking. The action of the tool is very similar to that of a hammer and the task involves generating repetitive impact forces by striking the tool on to the roof surface, while the roofer is standing on an inclined surface.

Ergonomic guidelines for power grip design have proposed a shape for the tool handle which should conform closely to the internal grip surface of the hand and have specified frictional characteristics of the handle to enhance gripping efficiency. A compressible grip material would increase the contact area thus minimizing pressure on the surface of the hand and reducing slippage (Konz and Johnson, 2008). Additionally, since grip strength is diminished when the wrist is flexed (Konz and Johnson, 2008); guidelines suggest that the wrist-tool coupling angle be maintained as close as possible to a neutral posture (handshake position) during the tool operation.

1.2 Research Objective

The objective of this study was to evaluate the effectiveness of the ergonomic guidelines for handle design of impact type hand tools. Three hammer stapler tools were selected from among several commercially available models. The chosen tools have employed the same stapling mechanism, essentially the same overall size, weight and staple pin size, but differ progressively in terms of grip characteristics.

A simulated roofing installation task was set up in a laboratory setting, where these three tools would be used. While working with an individual tool, the biomechanical and physiological responses would be monitored in terms of (1) muscular activity of the arm muscles by surface electromyography, (2) instantaneous wrist angles employing an electrogoniometer, and (3) heart rate employing electrocardiography. Additionally, subjective ratings of body discomfort resulting from the experimental task, and subjective rating for ease of use, comfort of grip and risk of injury from tool use would also be collected. The results would be analyzed to determine the degree of effectiveness of the ergonomic guidelines of hand tool design. Additionally, the results of the study would provide a set of quantitative biomechanical and physiological data for this task, which could be useful in future tool and job design.

CHAPTER 2

LITERATURE REVIEW

2.1 Epidemiology Of Hand Tool Use

The use of non-powered hand tools can contribute to upper extremity injuries of the hand, finger, wrist and shoulder. A study on injuries caused by hand-tool use conducted by the Bureau of Labor Statistics in 1996 revealed that hand tool injuries account for 9% of industrial injuries. Non-powered tools caused 80% of hand tool injuries and were related to 3.9% of amputations and powered tools caused 5.1% of amputations. A surveillance study conducted by NIOSH in1993 reported that musculoskeletal injuries accounted for 24% of all injuries caused by hand tools (power and non power). Many risk factors are directly related to the design of hand tools and to the methods employed when one uses them. Hence, inadequate tool design, improper use of a tool or improper selection of a tool can increase or generate excessive biomechanical stresses (Chaffin et al. 1999).

2.2 Pathology

2.2.1 Acute Trauma

Poor hand tool design may lead to anatomical and/or physiological trauma in the form of acute trauma or cumulative trauma. Acute trauma occurs immediately when a hand tool intrudes upon human tissue and includes Abrasion, Laceration, Contusion, Incision, Puncture, Fractures, Dislocations, Sprains, Strains, and Burns. The immediate nature of acute trauma simplifies the identification of the origin of the injury enabling the development and implementation of an effective means to prevent recurring injury of similar origin.

2.2.2 Cumulative Trauma

In contrast to acute trauma, cumulative trauma, also referred to as Musculoskeletal Disorder (MSD), is the result of a gradual buildup of trauma to muscle and tendon tissues when a tool is used for long durations in the presence of harmful interacting risk factors. MSDs are medical conditions where muscle, bone, cartilage, tendons or ligaments do not function in a healthy manner. The three major types of MSDs are tendon disorders, nerve disorders and neurovascular disorders.

2.2.3 Tendon Disorders

Tendon disorders occur in two types of tendons: those with sheaths and those without sheaths. Tendinitis is an inflammation of the tendons without sheaths brought on by repetitive awkward postures, forceful exertions or vibrations. Tenosynovitis is an inflammation of the tendon sheath which is like a sleeve through which the tendon slides. Cells inside the sheath inner wall produce a lubricating fluid for the tendons. Repetitive or excessive movements such as hand twisting and forceful gripping may cause this lubrication system to fail resulting in friction between the tendons and their common sheath. This creates an abnormal thickening and constriction of the sheath which interferes with the smooth gliding motion of the tendons causing inflammation. Another type of tendon disorder occurs when the tissues surrounding certain joints become inflamed and swell up with lubricating fluid from the tendons. Known as ganglion cysts, they form a small bump under the skin and are most common on the back side of the wrist and fingers though they can also develop in the shoulder, elbow, knee, hip, ankle and foot. Repeated strain on the forearm near the medial or lateral epicondyle of the humerus causes epicondylitis, a painful and sometimes disabling inflammation of the muscle and surrounding tissues of the elbow. The most common sites for tendon disorders are the shoulder, elbow, wrist, and thumb. Inflammation of the tendons that rotate the upper arm (humerous) and help raise the arm is called rotator cuff tendonitis. Bicipital tendonitis is inflammation of the tendon that connects the shoulder to the bicep muscle. Epicondylitis involves the elbow as previously discussed. DeQuervain's Disease, one of the most common and painful kinds of tenosynovitis, affects the tendons at the base of the thumb.

2.2.4 Nerve Disorders

The second type of MSD is nerve disorder. The human body has three types of nerves:

1. Autonomic nerves which control the involuntary or partially voluntary body functions such as heart rate, digestion and breathing;
2. Motor nerves which control voluntary movements by passing signals from the brain to the muscles via the spinal cord;
3. Sensory nerves which relay pain and other sensations from the skin and muscles back through the spinal cord and to the brain.

The symptoms that are associated with sensory nerve damage consist of pain, sensitivity, numbness, tingling or prickling, burning and problems with positional awareness. It is these sensory nerves that are most at risk from trauma or compression that result in nerve pain and nerve damage. Pinched nerves in the neck, the sciatic nerve in the low back, and the median nerve in the carpal tunnel are common disorders involving the sensory nerves. The carpal tunnel is a narrow passageway through the wrist which protects the median nerve and nine tendons that bend the fingers. Repetitive awkward posture of the wrist may irritate the tendons causing them to swell and compress the median nerve. Pressure on the nerve produces tingling or numbness, pain radiating from the wrist up to the shoulder, and eventually the hand weakness.

2.2.5 Neurovascular Disorders

Neurovascular disorders, the third type of MSD, pertain structurally and functionally to both the nervous and vascular structures. Thoracic outlet syndrome, which gets its name from the space between the collarbone (clavicle) and the first rib (the thoracic outlet) has symptoms consisting of neck, shoulder, and arm pain, numbness, and/or impaired circulation to the extremities. It derives from the compression of nerves or blood vessels, or both, that pass from the neck into the arms and blood vessels that pass between the chest and upper extremity. It can be caused by enlargement or movement of the tissues of or near the thoracic outlet. Thoracic outlet syndrome can result from injury, disease, or a congenital abnormality.

2.3 Ergonomic Evaluations of Hand Tool Characteristics and Utilization

Jung et al. (2005) showed that the application of ergonomic guidelines increases the efficiency and usability of manual hand tools in a study entitled "Ergonomic redesign and evaluation of a clamping tool handle". In this study, the handle of a commercial bar clamp was redesigned applying ergonomic principles and then compared to an original clamp in simulated clamping tasks under various conditions. These conditions included different clamping heights, clamping methods, and handle-gripping methods, with respect to the dependent variables of clamping and handle-squeezing forces. The results showed that the redesigned clamp produced larger clamping force with lower handle-squeezing forces than the original clamp. The modifications that were made to the original clamp consisted of the following: The length of the handle was increased from 80mm to 125mm to accommodate the 95th percentile male handbreadth, even when wearing gloves. A cylindrical shape was adopted to maximize contact area and reduce concentrated pressure between handle and hand. Flanges were added at the tip of the new handle to avoid slippage and allow the user to partially relax the hand between grips to close the clamp. Clamping force was measured with an S-type load cell and grasping force was measured with a miniature load cell. Both load cells were wired to a DAS-1701AO board installed in an IBM compatible PC. Data acquisition software, TestPoint, was used to display and save force data at a sampling rate of 10 Hz for 10 seconds. Both load cells were calibrated with known weights prior to the test. It was found that clamp, clamping method, gripping method, and gender all had significant effects on both peak clamping forces and peak handle-squeezing forces. The ratios for both redesigned and original clamps were approximately 0.55 and 0.34, respectively. Therefore, it could be concluded that the redesigned clamp was more efficient and caused larger resultant clamping forces, especially in pistol-type clamp usage.

In "An evaluation of arborist handsaws" Mirka et al. (2009) eighteen participants performed a simple sawing task at three different heights using six different arborist handsaws. Measurements consisted of recording EMG activity of the flexor and extensor digitorum, biceps brachii long and short heads, posterior deltoid, infraspinatus and latissimus dorsi; wrist posture at the beginning and ending of the sawing stroke, the time to complete the sawing task and a subjective ranking of the six different saws. A digital photograph was taken of the wrist angle at the end of the cutting stroke. The participants rank ordered the six different saws in terms of comfort, speed, and perceived accuracy. The results showed that as the work height increased, the biceps muscles increased their activation levels while the posterior deltoid activity decreased with the higher location. There was also a reduction in ulnar deviation as a result of the bent handle design. The MANOVA results for the muscle activation levels showed a significant effect of both SAW and HEIGHT but not their interaction. There were no consistent trends in these muscle activation profiles that indicated that one saw was superior to the others. The effects of HEIGHT were more pronounced and formed consistent trends. As the height increased from elbow to shoulder height, the activation of the extensor digitorum, both biceps and infraspinatus showed significant increases while the activation of the posterior deltoid showed a significant decrease. Results showed only small differences in the biomechanical responses among the saws but showed significant effects on subjective responses and productivity – with those saws that showed high levels of productivity also showing the better subjective assessments.

In "Biomechanical Assessment of New Hand-Powered Pruning Shears" Roquelaure et al. (2004) the biomechanical strains on the hand-wrist system were studied during grapevine pruning using newly designed pruning shears. The objective of the study was to assess the musculoskeletal load on the hand–wrist system during pruning with the new model of hand-powered pruning shears in comparison with standard pruning shears. The main characteristic of the new pruning shears is the vertical inclination of the blades which have been designed to attempt to reduce ulnar deviation of the wrist during cutting. The cutting head is also slightly tilted to the left to compensate for lateral bending. Another important characteristic compared to the reference pruning shears is the rotation of the lower handle. Surface electromyography of the finger flexor muscle and wrist postures were analyzed in four vineyard workers during actual work with the new and reference hand-powered pruning shears.

Video recordings, surface EMG and wrist movements were recorded during pruning in real working conditions. Each of four workers cut one row of 15 consecutive vine stocks with one of the pruning shears and, after a rest period of 5 min, a second row with the other pruning shears. The frequency of cuts was expressed as the number of sEMG peaks per minute. The total number of cuts analyzed was 1324 and 1137 for the new and reference pruning shears, respectively.

The mean cutting rates did not differ between pruning shears for all subjects. The mean sEMG activity of the flexor digitorum muscle varied considerably between subjects, ranging from 17.2% to 26.7% MVE with the new pruning shears and 24.0–25.1% MVE with the reference pruning shears. The difference was not statistically significant. The sEMG activity was significantly less than 15% MVE with the new pruning shears. The incidence of ''extreme'' wrist deviation did not significantly differ between the two types of pruning shears. The use of the new pruning shears was associated with a higher frequency of ''neutral and moderate'' U/R deviations and, to a lesser extent, of ''neutral and moderate'' F/E deviations.

In “Electromyographic and subjective evaluation of hand tool: The example of mason’s trowels”, Strasser et al. (1996) conducted a study to evaluate an ergonomically designed handle of a mason's trowel in comparison with two standard types because it has not achieved general acceptance in the trade. All the tools were equipped with the same blade. The participants in the study performed six separate work simulations with all three tools. Session 1 simulated the mixing of mortar with the help of a guideway rail in the shape of a figure eight. Session 2 simulated taking the working material out of hod #1, whereby the blade had to be inserted at an angle into the sand in 30 specific areas, and then to transport the material to point H of hod #2, where the sand after pronation of the right arm and the blade fell through a grid into hod #2. In session 3 the subjects had to hold the trowel with a horizontally aligned blade both with an external load of 0.9 kg and without any load for 30 s each. While doing this, they had to stand erect and hold their right upper arm in an abduction of 30° with horizontally aligned forearm. After a break of 120 s, several trials followed during which again with and without load a static position of 90° pronation and supination, respectively, was demanded. In session 4 rotational motions of up to 90° each via pronation and supination were demanded. Session 5 required scooping movements on a trajectory for an exact simulation of throwing mortar onto a vertical wall. In the final session (session 6) the subjects had to stand laterally and parallel to the mortar container and had to take the sand out of 30 indicated areas and throw it, with a rotatory scooping movement, onto a vertical wall within a specified range of height. This motion had to be repeated 30 times, again starting with a supination and then continuing with an accelerating pronation of the forearm. The motion was simultaneously accompanied by an adduction and abduction of the upper arm. Each trowel was then subjectively assessed by each participant used the same questionnaire as at the beginning of the testing. The strain of the 4 monitored muscles was expressed in percent of the maximum EA activity for the task of "mixing of mortar". Lower EA values of the biceps, significant at $p<0.05$, were measured when working with the ergonomic trowel 3 than when working with trowel 1. Ulnar and radial deviations during the figure 8 task are lower for the ergonomic handle H3, and in contrast to H1, they are essentially associated with significantly lower EA values of the extensor carpi ulnaris. In considering the physiological cost associated with the 3 versions of the trowels, favorable results were yielded in most of the cases with trowel 3, the ergonomic trowel. There were significantly lower EA values for the muscles involved in ulnar deviation and for the pronator teres. Conversely, no clear differences regarding the type of grip can be proven for the muscular strain of the biceps during pronation and during holding the blade horizontally. On the other hand, the ergonomic handle causes a higher level of strain on the biceps during muscle-specific supination, which is significant at least without external load. Concerning the remaining 3 muscles, the ergonomic trowel H3 turned out to be more favorable, especially for inward rotations of the blade, (i.e. pronations). Highly significant differences ($p < 0.001$) can be revealed for the muscle involved in ulnar deviations of the hand (i.e., the extensor carpi ulnaris) for all 8 possible comparisons between trowel 3 and the two other tools. In the scooping movements and movements involved in throwing mortar and sand, there were no systematic differences for the pronator teres, which is specifically involved in this movement. The results from session 6 do not support the experimental hypothesis thus the ergonomic grip does not always turn out to be favorable. Reduced physiological cost could not be found in every respect and to the extent subjectively expected. The subjective evaluations of the 3 handles clearly are in favor of the ergonomic trowel. However these are opinions and they do not derive from an adequate reduction of physiological cost during work. The ergonomic handle proved to be better than the standard models; however it was not found to be two or three times as good as is suggested by the results from several items of the questionnaire.

In “Bent Hammer Handles” (Konz and Streets 1984) a study was conducted to investigate the affects of bent handles for hammers. They used hammers with handles of 10° and 15° bends as well as a 0° bend Stanley hammer as the reference. Nails were driven into a pine board which lay flat on a table. The subjects consisted of 60 male college students who drove in 10 nails each. Hammer preference was estimated by rating each of the three hammers on a scale of 1 to 10, with 10 being the best. Each nail was measured for depth into the wood and for angle from vertical on left-right axes and front-back axes. There was no significant difference in the nail depth among the three hammers. The angle of the nail both right-left and front-back also had no significant difference. The 10° hammer was significantly preferred over the other two hammers however there was no significant practical difference.

CHAPTER 3

EXPERIMENTAL METHODOLOGY AND DATA COLLECTION

3.1 Participants

Volunteer participants were solicited for this study by posting fliers on bulletin boards throughout the NJIT campus buildings. The first 16 volunteers with no pre-existing musculoskeletal or cardiopulmonary illnesses contraindicated for the study, participated in this study. All participants were adult, able-bodied males. The participants were given a brief overview and demonstration of the experimental procedures and signed a consent form before participating in the experiment (Appendix A). The consent form described the purpose of the study, the tools and the methods utilized in the experimental trials. Participants were paid at a rate of $10 per hour. The participants consist of a cross section of students from NJIT who's anthropometric and demographic data are listed in Table 3.1. Their ages ranged from 19 to 30 with an average age of 22 years. Participant height ranged from 173 cm to 198 cm with and average height of 177 cm. Body weights ranged from 57 kg to 139 kg with average weight of 80 kg.

Table 3.1 Anthropometric and Demographic Data of Participants

Participant	Age	Weight (kg)	Height (cm)
1	28	66	173
2	22	79	180
3	21	91	183
4	30	63	183
5	19	105	198
6	25	61	180
7	20	76	178
8	24	57	175
9	19	91	178
10	19	74	169
11	19	139	175
12	21	86	183
13	19	70	169
14	21	76	183
15	24	86	160
16	23	75	173
Average	22	80	177
Standard Deviation	3.36	19.96	8.37

3.2 Tools and Materials

3.2.1 Hand Tools

After studying the existing commercially available hammer stapling tools in the retail market, three tool models were selected for the purpose of ergonomic evaluation of tool characteristics (Figure 3.1). The model HT50 (figure 1a) and HTX50 (figure 1b) were manufactured by Arrow Corporation and the model PC2K was manufactured by Bostitch Corporation. Henceforth these tool models will be referred to as Tool 1, 2 and 3, respectively in the rest of this thesis.

The tools 1 and 2 had identical length and weight, 28.27 cm (11.13 in.) and 0.953 kg (2.1 lbs) respectively. The Tool 3 had slightly longer overall length 36.19 cm (14.25

in.), and weighed 0.998 kg (2.2 lb). Essentially, the three models had comparable physical characteristics in terms of weight, magazine capacity and staple size, but possessed different combinations of ergonomic characteristics in terms of grip surface materials (rigid plastic and compressible rubber), grip cross-sectional shapes (rectangular and oval) and grip angles (straight and bent). All three tools have the same staple capacity of 168 ½-inch or ¼-inch staples.

(a)	(b)	(c)
Length: 283 mm)11.13 inches) Weight 2.1 lbs. (0.95 kg) Grip Height = 36.5 mm Grip Width = 31.75 mm	Length: 283 mm (11.13 inches) Weight 2.1 lbs. (0.95 kg) Grip Height = 40.5 mm Grip Width = 33.34 mm	Length: 361 mm (14.25 inches) Weight 2.2 lbs. (1.00 kg) Grip Height = 36.5mm to 38.10 mm Grip Width = 33.34 mm

Figure 3.1 Hammer stapler tools used for the study

The Tool-1 configuration was rudimentary, incorporating a straight handle with rigid plastic grip of rectangular cross section. The rectangular cross section was designed to prevent axial rotation of tool within the grip. The cross-section along the length of the grip was uniform and a series of crosswise groves on the rigid plastic covering was incorporated to prevent axial movement of the tool within the grip during stapling operation. The straight handle incorporated a 90° angle between the grip axis and the strike surface.

Tool-2 had a similar straight handle and grip cross section size and shape, but added two shields at the front and the back of the grip. These shields may prevent axial movement of the tool during stapling operation as well as provide safeguards from fingers being pinched between the strike surface and the grip. The grip material on the top of the handle was smooth, hard plastic but with no serrations. The bottom of the grip was a smooth hard rubber material.

Tool-3 incorporated three significant changes in grip characteristics. (1) The grip cross section was oval and was covered with resilient rubberized material. Oval cross-section prevents axial rotation of the tool within the grip, which may also be supplemented by the higher friction coefficient obtained from the resilient rubber material. Furthermore, the resilient rubber grip will increase the grip contact areas, thus reducing the contact pressure. (2) The cross-section along the length of the grip axis was gradually reducing from front to back of the grip. This prevents backward movement of the tool within the grip. Additionally such a shape conforms to the natural anthropometric shape of human grip. Since the difference in the lengths of the little finger and the middle finger is about 1 inch when fingers are curled around on to the palm to form a power grip, the diameter of the hole formed by the fingers gradually decreases from the index finger to little finger side of the grip (Konz and Johnson 2008). The section along the grip axis conformed to this shape. (3) Unlike the straight handle of the first two tools, this tool incorporated a 10° upward bend I the handle. When the fingers are curled in the form of a power grip, the base of the little finger is about 10° behind the base of the first finger (Konz and Johnson 2008). This angle is incorporated in the grip axis of the pistol grip tools, which compensates the wrist angle necessary to keep the tool straight. The bent grip axis in this tool would be expected to reduce the radial deviation of the wrist during the striking action. Figure 3.2 illustrates each tool positioned as it would be at the instant of optimum strike impact. Wider clearance aids in protecting the knuckles from being pinched or scraped on the roof surface.

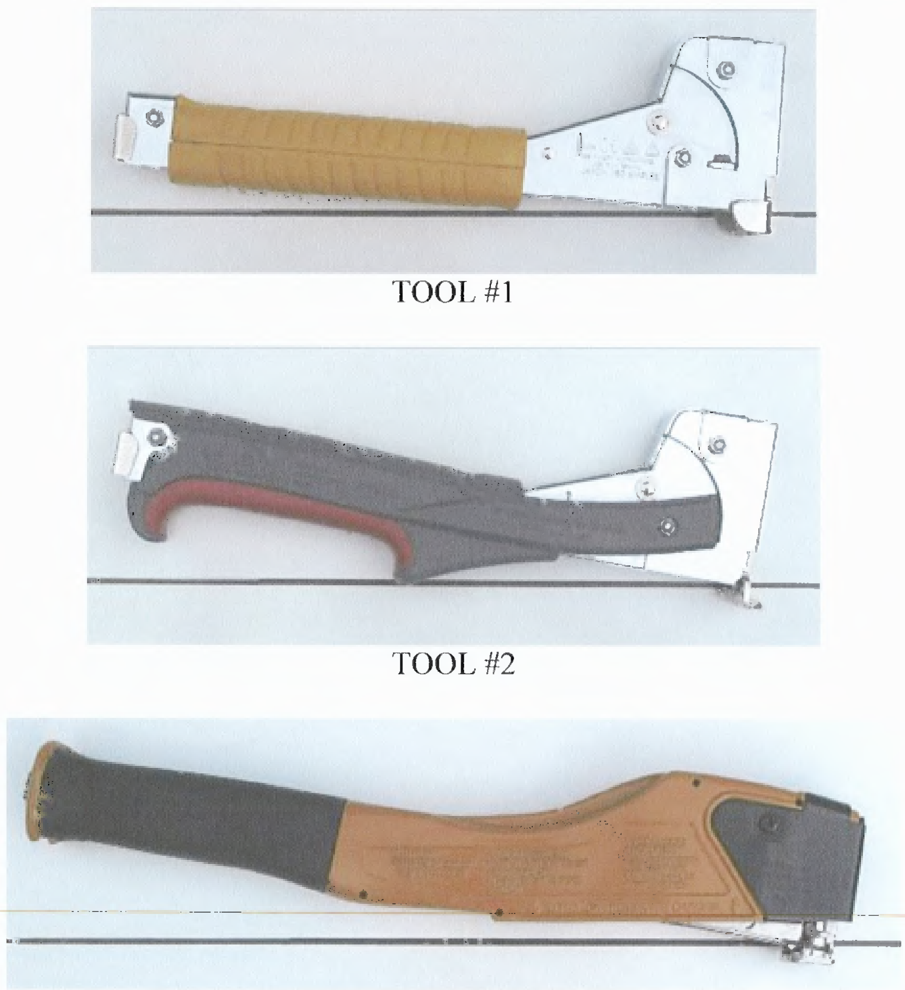

Figure 3.2 The clearance between the bottom of the tool handle and the roof surface (indicated by the black line) varies among the three hammer staplers.

3.2.2 Experimental Setup

A six-foot long by four-foot wide slanted platform was fabricated to simulate a typical roof surface encountered by roofing installers (Figure 3.3). It consisted of a platform constructed of a piece of 5/8-inch thick roof-grade plywood anchored to a wooden frame constructed of 2"x 4" joists set at 16-inch centers. Legs attached at one end of the platform created an incline of a 4-inch vertical rise for each foot horizontally otherwise referred to as a 4:12 pitch. A second platform constructed of plywood anchored to 2" x 10" framing provided a base unit upon which the first platform was placed to increase the roof pitch to 6-inch vertical rise for each foot horizontally, that is a 6:12 pitch. These two pitches are the most commonly found in residential roof pitches. Since the hammer stapler tool is used to attach roofing paper to the roof deck, a layer of black roofing paper was attached on to the platform to simulate the stapling task more closely.

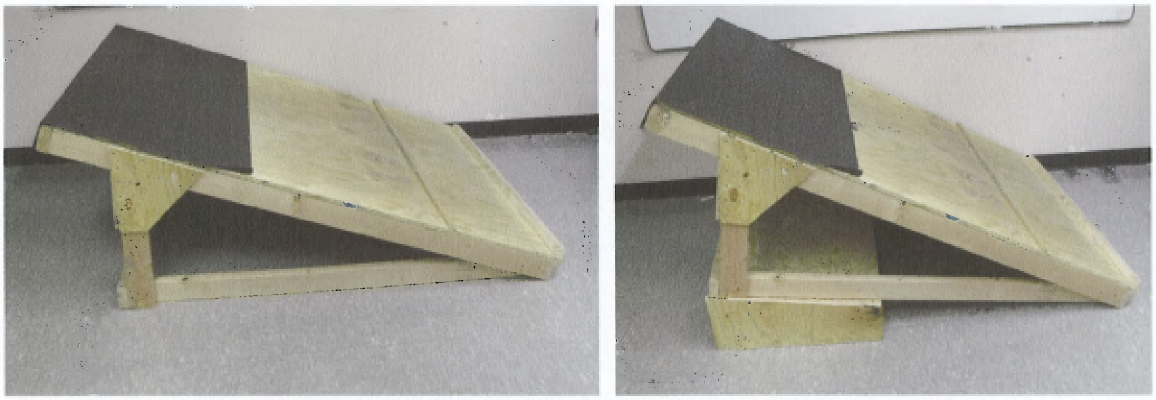

Figure 3.3 Test Platform (4:12 Pitch - Left, 6:12 Pitch - Right)

3.3 Simulation of Work Elements and Test Procedure

This study was conducted in the NJIT Safety Laboratory. A repeated measure experimental design was implemented for this study. The independent factors consisted of (i) two levels of roof pitch (4: 12 and 6:12) and (ii) the three stapling tools. Each participant was involved in six separate experimental trials involving the combinations of three different tools used on each of the two different roof pitches. The sequence of the trials was randomized to eliminate any bias occurring from the order of the trials.

Prior to the experiment, participants practiced with the hammer staplers to become familiar with the task. Each experimental trial consisted of stapling at a frequency of 1 staple per second for duration of two minutes. The pace was maintained by following an audible metronome signal set at one beat per second. The strikes were done in a pattern following the three rows marked by pre-printed lines on the roofing paper. The pattern consisted of striking the top row, the middle row and the bottom row and repeating this sequence while moving laterally from one side to the other, which was continued until the end of the two minute interval. During stapling operation, the participants were instructed to apply enough force to insert the staples entirely and flush with the paper. When inconsistency was noticed, participants were verbally reminded to maintain the accuracy. Stapling with the hammer staplers is a comparatively easy task to accomplish and inaccuracy was rare. Between the experimental trails, participants rested for 6 minutes to allow for recovery of any physical fatigue.

3.4 Measurement Instrumentation

3.4.1 Electromyographic Recordings

One of the primary goals of this experiment was to evaluate the effect of differences in the tool characteristics in terms of muscular strain. Electromyographic (EMG) activity was monitored on the three primary arm muscles while utilizing a hammer stapler. These muscles consisted of the Biceps Brachii in the upper arm and the Extensor Carpi Radialis Brevis and the Flexor Carpi Ulnaris in the forearm. Muscle activity was monitored with type SX230 bipolar differential surface electrodes, manufactured by Biometrics Ltd. These were adhered to the participant's skin with Biometrics Ltd's medical grade adhesive tape (Figure 3.4). The design of these electrodes includes a pre amplifier which

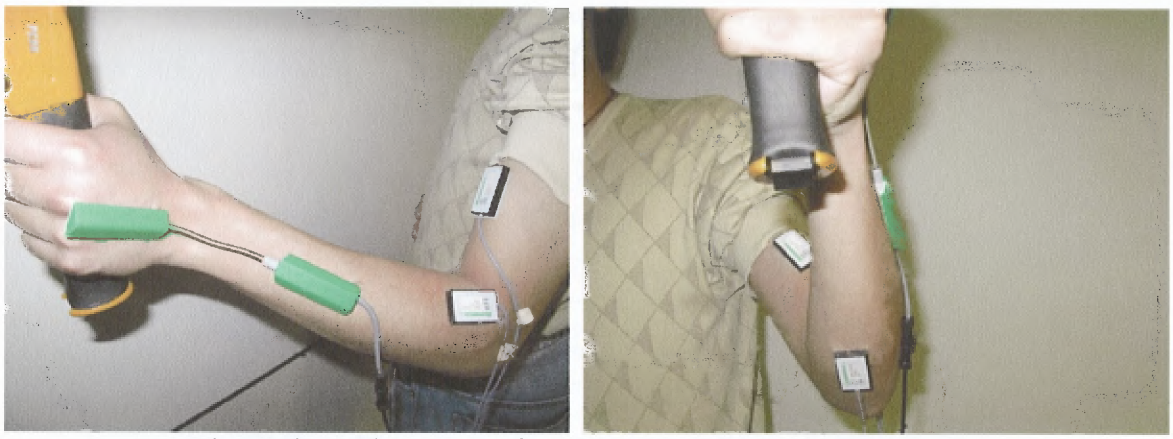

Figure 3.4 Placement of surface electrodes and goniometer

allows them to differentiate between the small signal of interest (around 1 μV) and the much larger interference signals that are present on the skin surface. The area of the skin where each electrode was placed was first cleaned and abraded and then electrode conductive gel was applied before attaching it to the participant's skin. The EMG activity was transmitted through an 8-channel remote patient data acquisition unit (attached to the participant's belt) to a DataLINK DLK800 Base unit (CE 0120 certified to IEC601-1). A personal computer operating BIOMETRICS DATALINK PC SOFTWARE Version 2.0 was connected to the DLK800 base unit and utilized to store the EMG data. The system configuration of the EMG data collection is shown in Figure

3.4. EMG activity was recorded at a rate of 1000 Hz for the entire duration of a trail and stored for further data analysis.

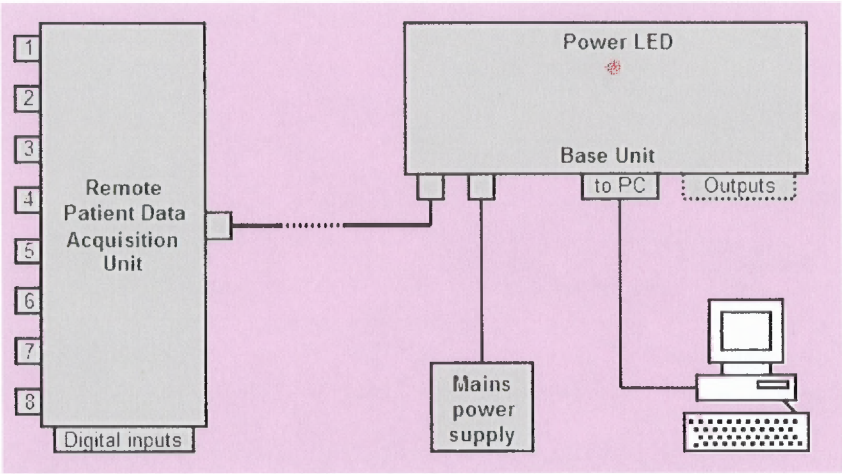

Figure 3.5 The Biometrics DataLINK hardware system configuration

3.4.2 Normalization Tasks for EMG

EMG for the maximum voluntary contraction (MVC) was recorded for each of the three muscles and later used to normalize the task EMG values. Each participant was instructed to hold the hammer stapler tool 3 with elbow flexed at 90° and wrist at the neutral posture so that the tool was in a vertical orientation. They were then instructed to restrain the tool with their free hand while performing maximum contraction of their Extensor Carpi Radialis Brevis muscle by attempting to rotate the tool towards them (the direction of radial deviation of wrist). They held the maximum contraction for a count of six followed by a rest. This sequence was repeated three times. This same procedure was then performed in the opposite direction (the direction of ulnar deviation of wrist) to obtain the MVC for the Flexor Carpi Ulnaris muscle. The MVC for the Biceps Brachii was measured by having the participant sit in a chair in front of a desk with their elbow flexed 90 degrees. With their fist placed underneath the edge of the desk surface they performed a maximum contraction of the Biceps Brachii following the same duration in used for determining the other two MVC's.

3.4.3 Electrogoniometer Recording

The instantaneous angular measurements of radial and ulnar deviations of the wrist were monitored at a rate of 1000 HZ and recorded during each experimental trial. The pre calibrated electrogoniometer, which is a part of the DataLINK system, utilized one channel of the DataLINK's data acquisition unit, and the instantaneous angular data were stored along with the EMG signals. The two end terminals of the electrogoniometer were affixed to the dorsal skin surface of forearm and hand by double sided adhesive tape and the goniometer reading was set to zero while the subject maintained a neutral wrist posture.

3.4.4 Heart Rate Measurement

A portable heart rate recorder manufactured by Polar (model number T-31) was utilized to store each participant's heart rate data during the experimental trials. The heart rate was monitored by a chest belt worn by the participant, which picked up the electrocardiographic signals and transmitted them wirelessly to a SmartSync heart rate recorder manufactured by Oregon Scientific. Heart rate data were collected for each trial and were later transferred to a personal computer for data analysis.

3.4.5 Body Discomfort Ratings and Subjective Evaluation of Tool Characteristics

A paper survey was developed to obtain the participants' ratings of body discomfort and tool safety (see Appendix B). Using the survey, the participants rated their perceived level of discomfort in ten key areas of the body. They used a scale of 0 to 10 where 0 represents no pain and 10 represents unbearable pain. The survey also included three safety related items consisting of "ease of use", "grip comfort", and "protection from injury", which were rated on a scale from 1 to 10 where 1 represents least favorable and 10 represents most favorable. Participants completed this survey immediately after each of the six trials.

CHAPTER 4

RESULTS AND ANALYSIS

All response variables are evaluated using the following two-factor analysis of variance (ANOVA) model with participant as blocks to determine the statistical significance effects at a p-value less than 0.05,

$$Y = \mu + \alpha\, T + \beta\, L + \gamma\, (T \times L) + \delta\, P + \varepsilon$$

Where,

Y is the response variable
T represents tool factor at three levels (T1, T2 & T3),
L represents roof inclination factor at two levels (High & Low),
P represents participants blocking factor (P1 to P16),
μ is the overall mean;
α, β, γ & δ are the main effects of the factors, and
ε is the error term.

Minitab 15, statistical analysis software was utilized to analyze the experimental data. Participant factor was used as a random blocking variable to filter out variations of responses stemmed from differences in participants. In all statistical tests, the participant factor effect was significant (p=0.00) which was expected. No interaction effect between tool and roof pitch inclination was significant for any response variable. Differences in the factor level means for the three tools were determined from Tukey's test of joint confidence interval at 5% level. The numerical details of ANOVA results can be found in Appendix C. The following sections discuss the analyses of the individual response variables.

4.1 Body Part Discomfort Ratings

After each experimental session, the participants rated their discomfort in relevant body parts on a scale of 0-10, with 0 being no discomfort and 10 being maximum discomfort. The averages and standard deviations with respect to each tool type are illustrated in Figure 4.1. The average scores were less than 2, which corresponds to "slight discomfort" sensation in the visual-analog scale. The individual ratings varied widely among the participants ranging from 0 to 9. Standard deviations of the scores were relatively high resulting in an overall average coefficient of variation of 158%. Such variations obviously came from difference in perception of visual analog categories among the participants. Among the upper extremities, fingers, wrist and forearm received higher discomfort ratings, possibly due to higher muscle contraction needed for gripping the tool, as well as, from the impact forces transmitted to these regions from the tool strikes. Upper arm, shoulder, neck and upper back average scores were relatively low. Since the task required the participants' torso to be maintained in a severely flexed posture, significant static muscle contraction at the lower back area was expected. Standing on a slopping surface in a stooped posture would also induce higher static muscle tension in the ankle and thigh regions. These factors correspond to the comparatively higher discomfort ratings at those regions.

A statistically significant difference in mean discomfort scores was found for fingers ($p=0.03$) and upper back ($p=0.06$). For both of these body regions, Tukey's joint confidence interval showed that the mean score of Tool 3 was significantly lower than Tool 1, but the mean scores of Tool 3 and Tool 2 were not different from each other, nor were the mean scores between Tool 2 and Tool 1. Roof inclination factor had no significant effect for any of the discomfort ratings.

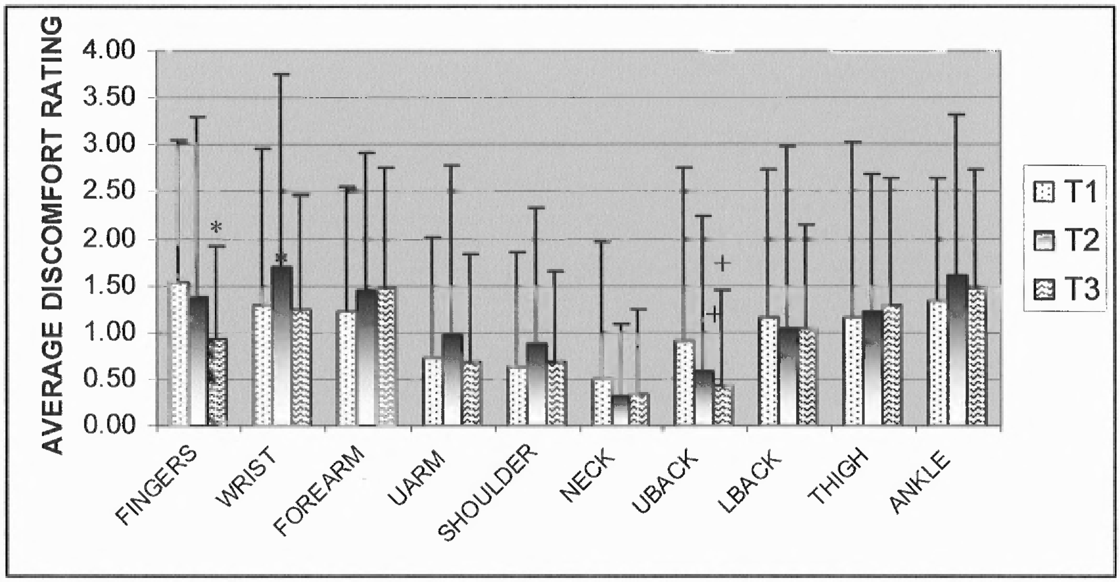

Figure 4.1 Comparison of discomfort ratings between Tool 1, Tool 2 and Tool 3.
Note: * denotes p-value = 0.03, + denotes p-value = 0.06.

4.2 Subjective Perception of Tool Characteristics

At the end of each experimental trial, participants rated their perception about the individual tool in terms of (1) ease of use, (2) grip comfort and (3) protection from injury, with a rating scale of 0 being least favorable and 10 being most favorable. Figure 4.2 shows the mean scores and respective standard deviations. In terms of ease of use, Tool 3 received significantly better ratings than Tool 2 and Tool 1, with p-values = 0.01. In terms of grip comfort, Tool 2 and Tool 3 were not different, but Tool 1 was rated significantly lower than Tool 2 (p=0.01) and Tool 3 (p=0.00). Similar statistical results were found for perception of protection from injury, i.e., no significant difference between Tool 2 and 3, but Tool 1 was rated significantly inferior compared to Tool 2 (p=0.00) and Tool 3 (p=0.00).

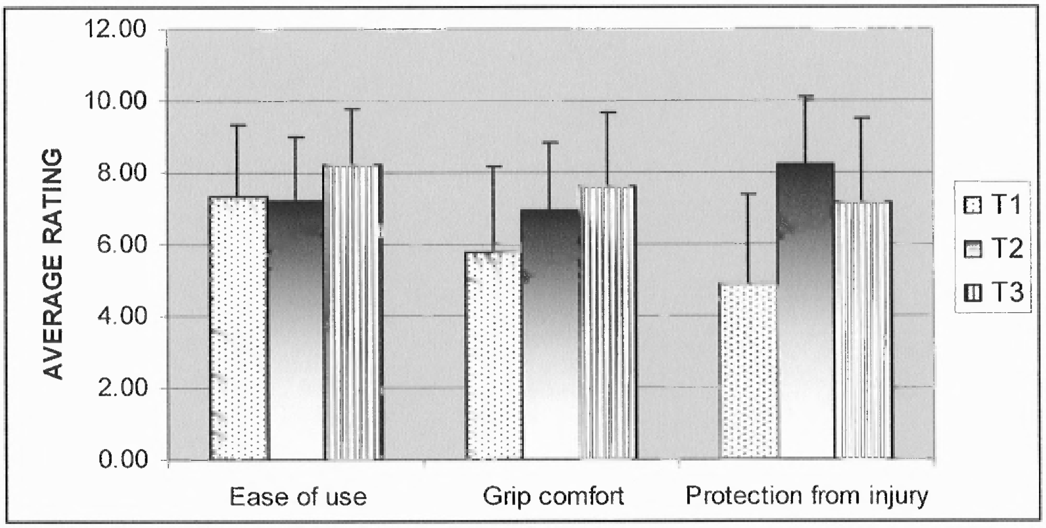

Figure 4.2 Comparison of tool safety ratings between Tool 1, Tool 2 and Tool 3

4.3 Electromyographic Activity (EA) of The Major Muscles Involved

The electromyographic activity (EA) of the three major muscle groups involved in performing the task was recorded continuously over the duration of each of the six trials for each participant at a rate of 1000 Hz. The typical EA registrations for each muscle are shown in the graphs in Figures 4.4 – 4.6 below. The graph in figure 4.4 shows the increase in recruitment of the Extensor Carpi Radialis Brevis to create the force exerted upon impact of the tool on the roof surface. This is followed immediately by relaxing of this muscle as seen in the graph by the drastic reduction in EA to the left of the tool strike. This muscle remains relaxed while the arm is raised up to prepare for the next phase of the tool strike cycle. The Flexor Carpi Ulnaris muscle contracts resulting in radial deviation of the wrist as the tool is raised to begin another cycle. The graph in Figure 4.5 shows the EA of this muscle.

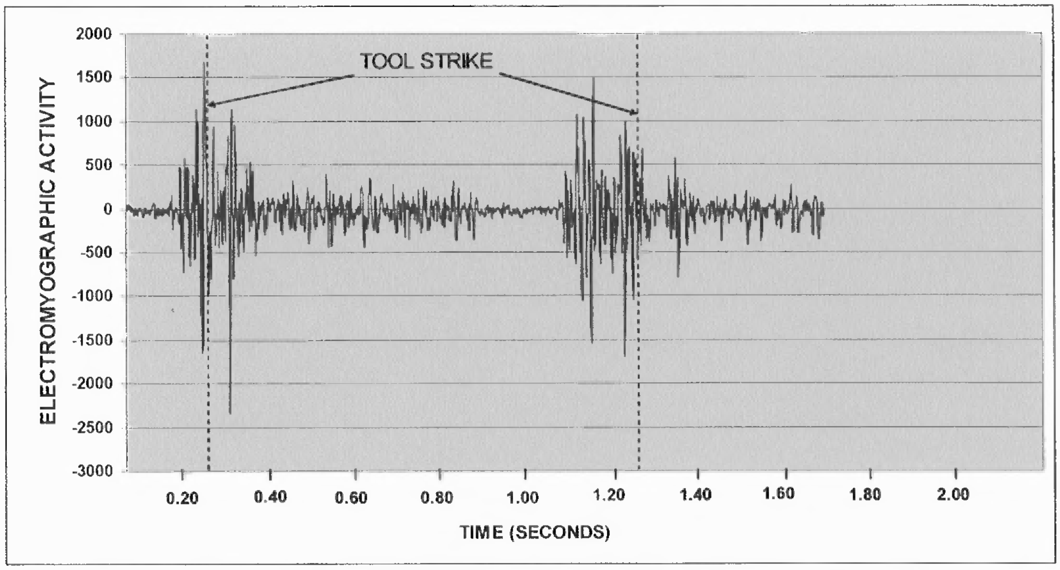

Figure 4.3 Typical Electromyographic Activity for Extensor Carpi Radialis

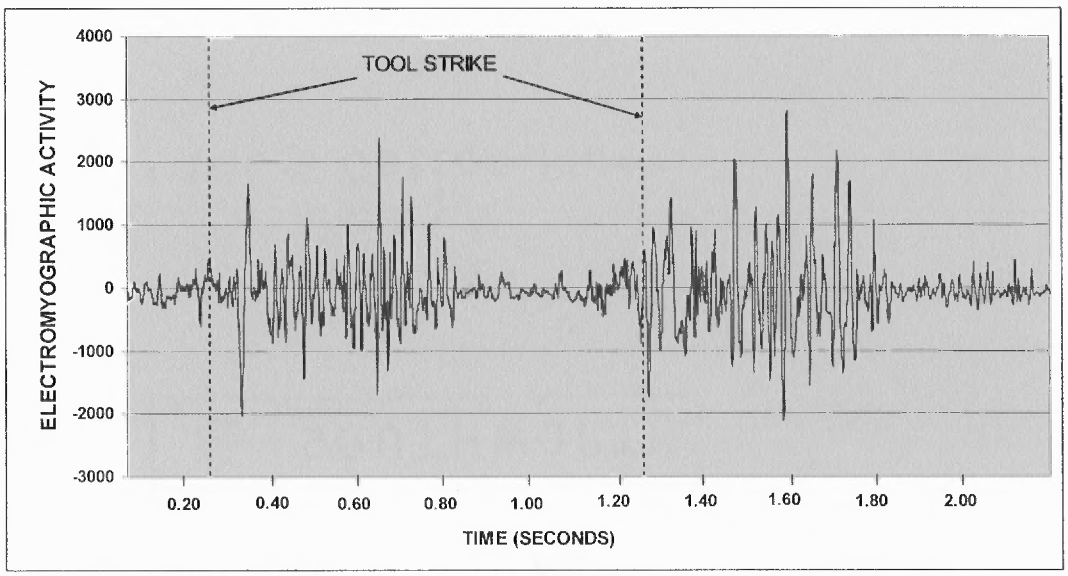

Figure 4.4 Typical Electromyographic Activity for the Flexor Carpi Ulnaris

Simultaneously, the Biceps Brachii muscle also contracts to flex the forearm and position the tool for the next downward strike. The EA of the Biceps Brachii is seen in figure 4.5.

The magnitude of muscle strain is expressed as a percentage of the maximum voluntary contraction (MVC) and referred to as the standardized electromyographic activity (sEA). The electromyographic activity (EA) that was recorded for each muscle

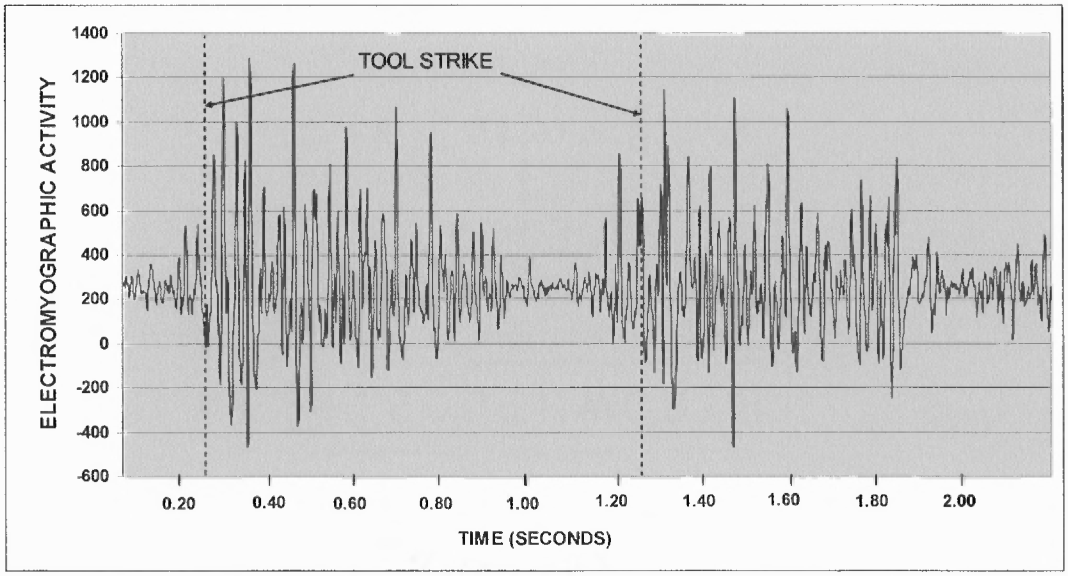

Figure 4.5 Typical Electromyographic Activity for the Biceps Brachii

during each task and during the MVC was first filtered by applying the RMS with a time constant of 200 mS. The sEA was then calculated using the following equation:

$$sEA = \frac{EA}{EA_{\max}} \times 100\,\%$$

sEA : Standardized Electromyographic Activity
EA_{max}: Activity during maximum voluntary contractions
EA: Activity during the task

sEA of the muscle groups were not significantly different for the roof inclinations. The graph in Figure 4.6 shows the average sEA of the muscle groups for each tool. The sEA of the Extensor Carpi Radialis Brevis was higher for Tool 3 than for Tool 1 or Tool 2. There is no significant difference between Tool 1 and Tool 2.

4.4 Angular Deviation of The Wrist

Wrist angles in ulnar and radial deviation were measured by the electrogoniometer. The electrogoniometer was set to zero at the neutral posture of wrist, and positive angles represented ulnar deviation and negative angles were radial deviation from this neutral

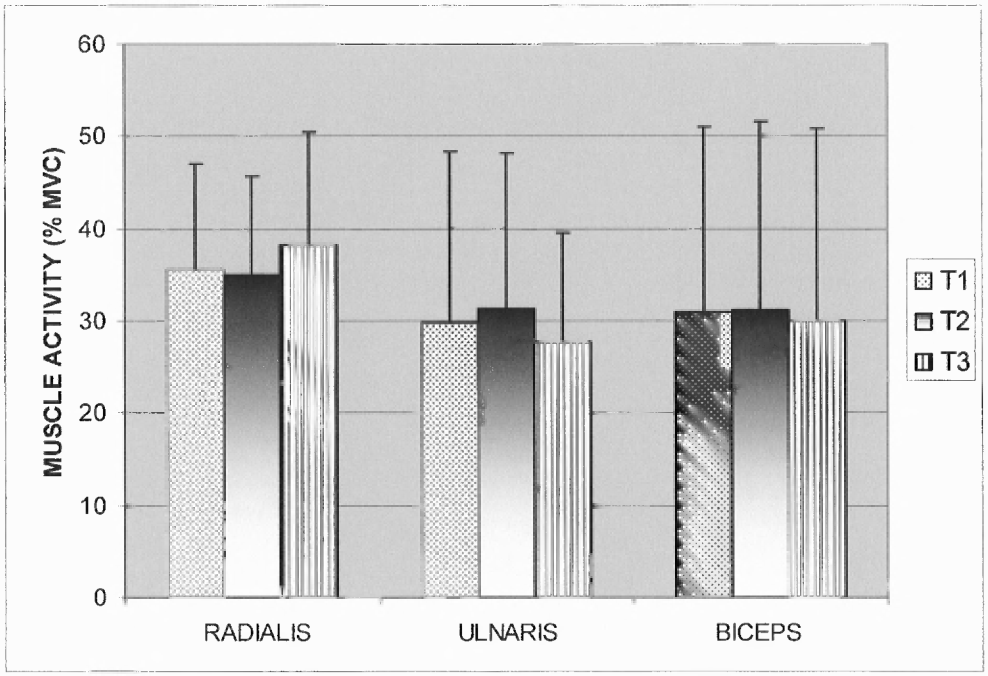

Figure 4.6 Mean Electromyographic Activity of the Muscle Groups

position. The participants were striking the tool at a rate of 1 strike per second and data was captured at a rate of 1000 Hz. The typical variation of wrist angle during the hammer stapler strikes are shown in Figure 4.7. The sharp vertical rise of the plot from negative to positive angle shows the downward motion of the tool accompanied by radial to ulnar deviation of the wrist. After the strike, the tool's upward motion is depicted by the downward sloping plot. Slope of the rise of the plot is much greater than the slope of fall of the plot of each cycle of operation, indicating that the downward striking velocity of the tool was greater than the velocity of lifting the tool up after the strike. Figure 4.8

shows a sample plot for approximately 30 strikes of an experimental session. It is apparent from the plot that the ulnar and radial deviations are varying considerably from strike to strike. There is some random variation from strike to strike, which can be attributed to natural and uncontrolled variation of wrist angles. Some systematic variation over the time can also be noticed, that might have occurred when the participant changed the distance of the stapling row as demanded by the experimental task. For the purpose of data analysis, we determined the 99 percentile, median and 1 percentile values of the

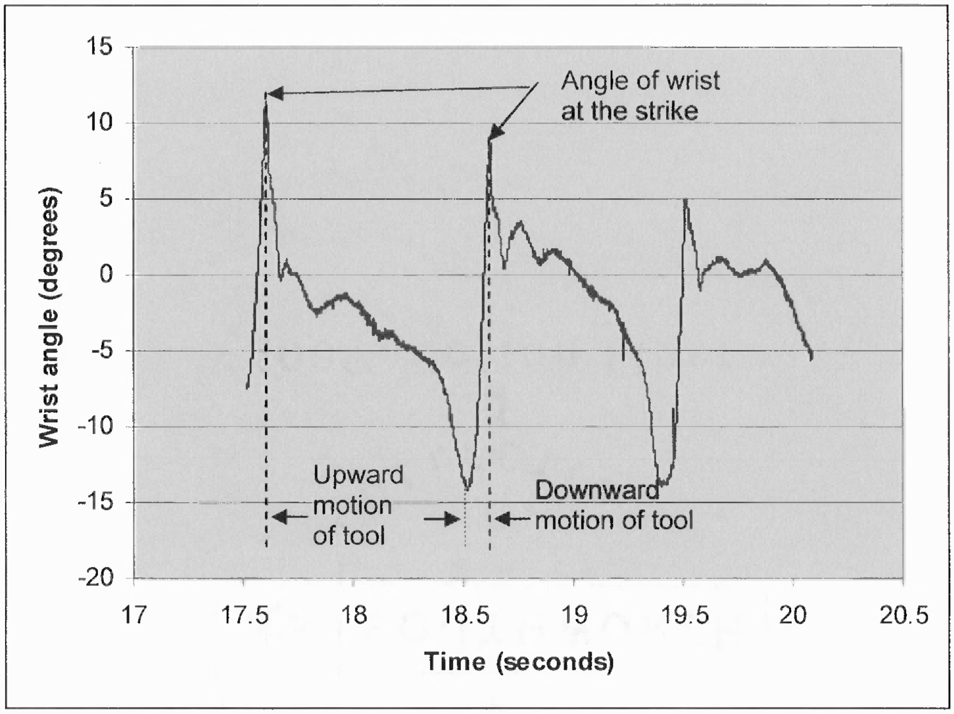

Figure 4.7 Typical variations of Wrist angles during the tool strikes

angles recorded in each experimental session. The 99 percentile value represented the characteristic ulnar deviation angles, median determined the median wrist angle maintained during the experimental trial and 1 percentile value represented the characteristic radial deviation during an experimental session. For the experimental task it was expected that the median wrist angle would be maintained close to neutral, ie., close to zero degree reading of the goniometer. However, inspection of the data revealed that that is not the case. Some participant's median angles were significantly different than zero, however, the majority of the participants' median angle was within plus or minus 10 degrees. The cause of this discrepancy could be from instrument error, or from the habitual atypical wrist posture of the subjects. For the purpose of goniometer data analysis, the later group was separated out and statistical tests were performed.

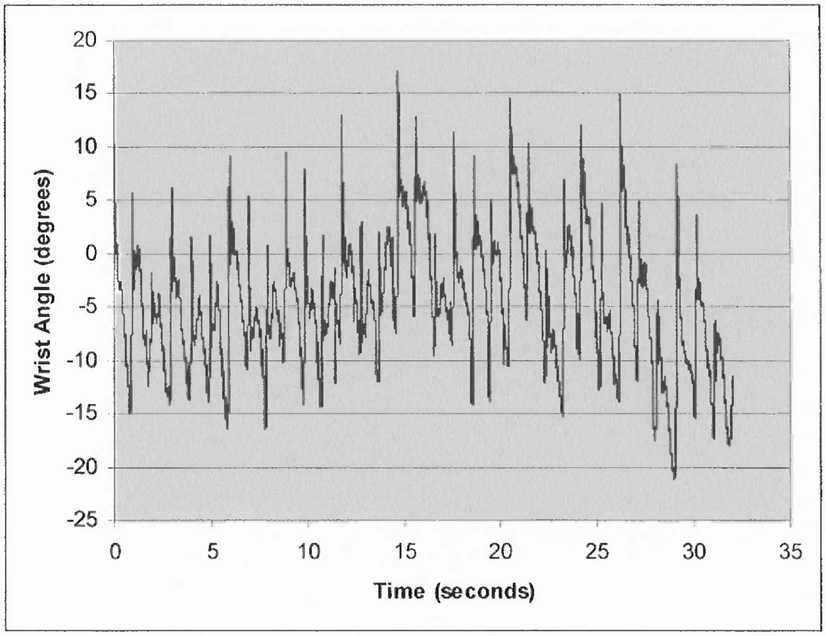

Figure 4.8 Sample plot of electro-goniometer data over 30 seconds

Figure 4.9 shows the mean and standard deviation of radial and ulnar deviations from the three tools. "Tool" had a significant effect on ulnar deviation ($p=0.034$), and "roof incline" was significant for radial deviation ($p=0.024$). Tool 3 produced significantly smaller ulnar deviation as compared to Tool 2 ($p=0.026$). No other contrast of means was significant.

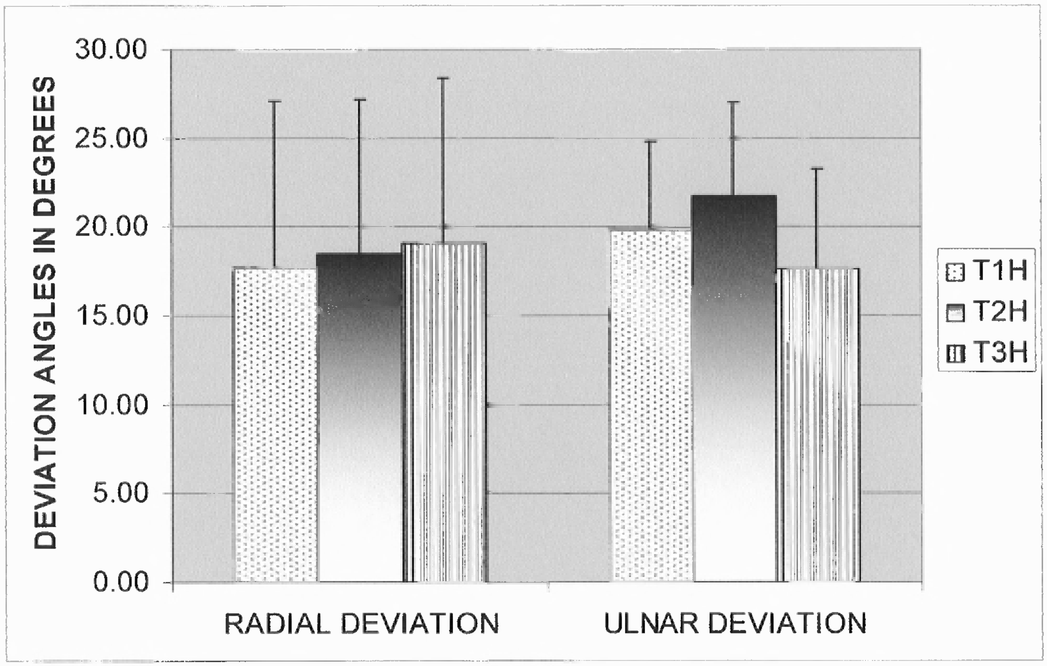

Figure 4.9 Radial and Ulnar deviations with respect to tools

From the biomechanical point of view, the wrist joint will be subjected to considerable impact force at the instant of tool strike, hence ergonomically speaking; the wrist angle at which it is sustaining the impact force is an important factor for causation of injury. Thus the 99 percentile value representing the ulnar deviation will be a more important factor in this evaluation. Ulnar deviation for Tool 3 was significantly less than Tool 2 ($p = 0.03$) on both roof pitches.

4.5 Heart Rate

The heart rate was recorded in beats per minute (BPM) every two seconds by the heart rate monitor. The graphs in figure 4.10 show the physiological response to the six experimental trials in terms of increased heart rate. The six experimental trials, identified by the six pairs of vertical lines, all have nearly identical maximum heart rates for participant 12. The graph for participant 16 also shows the maximum heart rate for each of the trials to be consistent. The percentage increase in heart rate was calculated using the following equation:

$$\% \text{ HR} = (\text{MAX. HR} - \text{RESTING HR}) / \text{RESTING HR}$$

There was no significant affect on the heart rate among the three tools as shown in Figure 4.11. The percentage increase in heart rate overall was significantly higher for the low pitch roof compared to the high pitch roof. This was expected due to the upper body leaning more forward on the low pitch roof than the high pitch roof. The additional recruitment of back muscles to compensate for this accounts for the higher percentage increase in heart rate. This result validates the experimental setup.

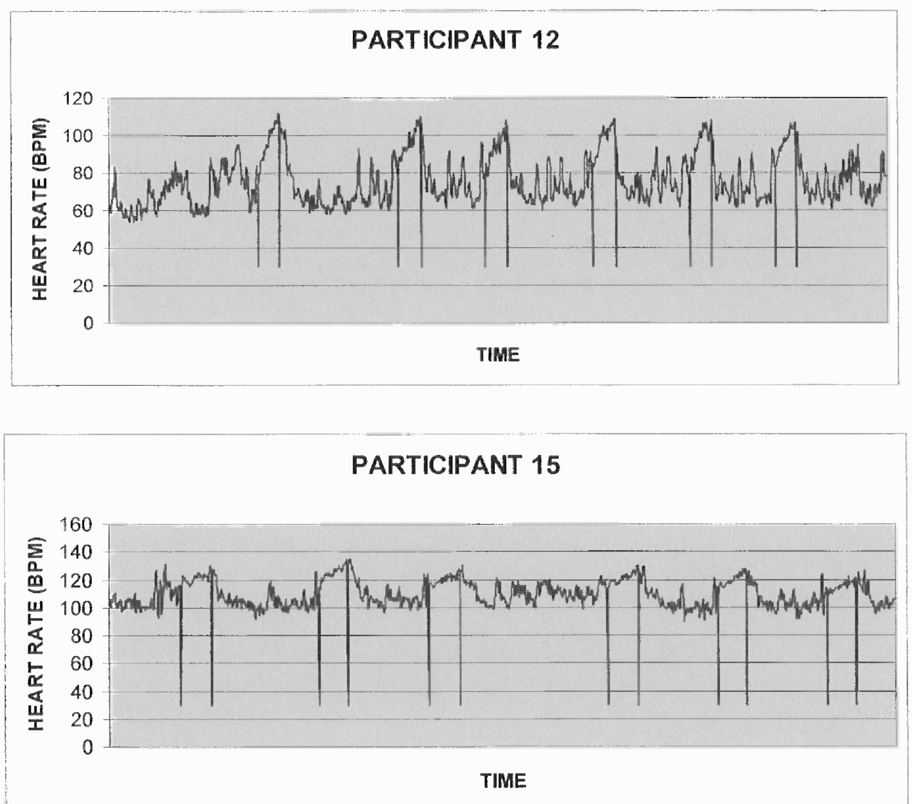

Figure 4.10 Graphs of typical heart rate during all six experimental trials indicated by the pairs of vertical lines

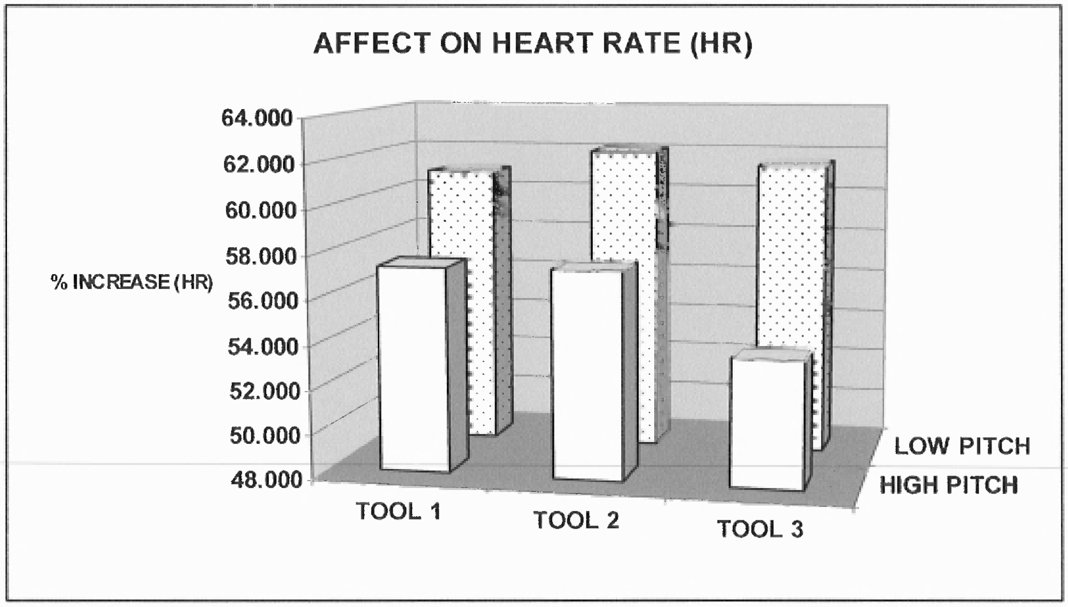

Figure 4.11 Tool and Roof pitch affect on heart rate (HR)

4.6 Discussion of Results

Ideally, a hand tool handle should be equipped with the following ergonomic design features: (Konz and Johnson, 2008)

- power grip diameter between 35mm to 45mm
- a cross-section with a good bearing surface to provide counter-torque and prevent the tool from rotating in the hand
- a change in cross-section to reduce movement of the tool forward or backward in the hand, to provide a better bearing surface which permits greater force to be exerted along the tool axis
- a soft rubber, compressible surface to improve the coefficient of friction, to minimize pressure on the hand by increasing contact area, and reduce vibration transmission to the hand.
- Minimal wrist angle using the tool – goal is to keep the wrist in the neutral position. The risk of cumulative trauma increases as the wrist angle increases

Tool 3 had the most favorable average subjective rating for both "Ease of use" and "Grip comfort". The compressible material that covers the handle of Tool 3 leads to an increase in contact area between the hand and the handle. This distributes the grip forces to a larger area thus reducing the contact pressure on the palm. Also, the end of the handle for Tool 3 tapers thus conforming to the contour of the hand in the power-grip position further adding to the ergonomic quality of the tool. Tool 2 was rated better than Tool 3 for "Protection from Injury" and both were rated better than Tool 1. The handle shape for Tool 2 includes a "knuckle guard" on the underside of the handle. This protects the knuckles from getting pinched between the tool handle and the roof surface at the instant of tool impact. The handle for Tool 3 has a 10° upward bend which results in raising the knuckles above the line of impact and also aids in protecting them from getting pinched.

The level of muscle activation for the Extensor Carpi Radialis Brevis was higher for Tool 3 than for Tool 1 or Tool 2. This may be due to Tool 3 being 0.05 kg heavier than tool 1 and Tool 2 and thus engaging more of that muscle. This muscle is associated with the ulnar deviation and the downward movement of the tool strike. It is theorized that as the tool is raised to its highest point in the cycle and the direction of the arm is instantaneously changed from upward to downward, the momentum of the tool places a force on that muscle. The additional weight of Tool 3 would result in higher forces on that muscle and account for the observed difference.

Angular deviation of the wrist was affected by the tool handle design. Tool 3 had the lowest ulnar deviation on both the low pitch and the high pitch roof. The 10° bend in the end of the handle of Tool 3 aids in keeping the wrist closer to a neutral posture.

The angle of roof incline affected heart rate as would be expected since the low pitch roof engages more back muscles due to bending forward further than on the high pitch roof. The heart rate increase is directly proportional to the level of muscle activity. Tool design had no affect on heart rate.

In looking at the findings from this study, the ergonomic differences between the three tools are significant with regard to surface materials, grip characteristics and hand protection features. The average subjective rating for Tool 3 was significantly better than the rating for Tool 1 regarding discomfort level in the fingers ($p = 0.03$) and in the upper back ($p = 0.06$). Tool 3 was rated significantly better than Tool 1 and Tool 2 regarding "Ease of use" ($p=0.01$) and significantly better than Tool 1 regarding grip comfort ($p=0.00$). Tool 3, as well as Tool 2, was rated superior to Tool 1 for Protection from injury. Ulnar deviation for Tool 3 was significantly less than Tool 2 ($p = 0.03$) on both roof pitches. The 10^0 upward angle of the Tool 3 handle was found to significantly reduce the ulnar deviation as well as aid in protection from pinching the knuckles / fingers at the instant of tool impact.

CHAPTER 5

CONCLUSION

The present study investigated grip characteristics of three different hammer staplers in terms of surface composition, cross-sectional size and shape, and wrist deviation related to tool use. Sixteen participants performed a work-simulated task in six different combinations of tool and roof incline in a laboratory setting. EMG, wrist deviation, heart rate, body discomfort, and tool safety perception were measured to quantify the effects of the grip characteristics. In terms of ergonomic design features, all three tools have a grip diameter between 35mm and 40mm and a cross-section that provides counter-torque to prevent the tool from twisting in the hand. Tool 3 however is equipped with additional ergonomic features consisting of a varying cross-section, a soft rubber compressible surface and a 10^{o} bend in the handle. Subsequently, Tool 3 was rated significantly easier to use ($p=0.01$), had the lowest level of discomfort in the fingers and hand ($p=0.05$), the highest rating in grip comfort ($p=0.05$), the highest rating in protection from injury ($p=0.05$), the lowest muscle demand for one of the muscles monitored ($p<0.05$) and the lowest wrist deviation ($p<0.05$). Clearly, the ergonomic features served the purposes for which they were designed. This study supports the Konz & Johnson (2008) findings that hand tool handles should be equipped with ergonomic design features listed in section 4.6. Future hand tool design would benefit from the quantitative data resulting from this study.

APPENDIX A

INFORMED CONSENT FORM

NEW JERSEY INSTITUTE OF TECHNOLOGY
323 MARTIN LUTHER KING BLVD.
NEWARK, NJ 07102

CONSENT TO PARTICIPATE IN A RESEARCH STUDY

TITLE OF STUDY:

THE EFFECT OF HANDLE CHARACTERISTICS OF A HAMMER STAPLER TOOL ON BIOMECHANICAL AND PHYSIOLOGICAL RESPONSES

RESEARCH STUDY:

I,____, have been asked to participate in a research study under the direction of Dr. Arijit Sengupta. Other professional persons who work with them as study staff may assist to act for them.

PURPOSE:

To investigate the effects of improved grip surface, grip shape and grip angle of hammer staplers in terms of biomechanical and physiological responses.

DURATION:

My participation in this study will last for approximately ___2 hours__________.

PROCEDURES:

I have been told that, during the course of this study, the following will occur:

I will be asked to fill out my contact information and questionnaire pertaining to my current physical well being and fatigue and stress levels prior to testing.

PARTICIPANTS:

I will be one of about ___16_____participants in this study.

EXCLUSIONS:

I will inform the researcher if any of the following apply to me:

- If I am not of the age of 18 or over the age of 45.
- If I have had any acute or chronic pain or weakness on upper or lower body.
- If I have a weak heart, shortness of breath, dizziness, or am diagnosed by a doctor that I should not be working for extended periods of time.
- If I have an allergic reaction to adhesive tape

RISKS/DISCOMFORTS:

I have been told that the study described above may involve the following risks and/or discomforts:

I may experience minor muscular soreness in forearm, lower back or thigh a few days after completing the study. Other discomforts may include wrist and shoulder pain, blisters, and broken finger nails.

I fully recognize that there are risks that I may be exposed to by volunteering in this study which are inherent in participating in any study; I understand that I am not covered by NJIT's insurance policy for any injury or loss I might sustain in the course of participating in the study.

CONFIDENTIALITY:
I understand confidential is not the same as anonymous. Confidential means that my name will not be disclosed if there exists a documented linkage between my identity and my responses as recorded in the research records. Every effort will be made to maintain the confidentiality of my study records. If the findings from the study are published, I will not be identified by name. My identity will remain confidential unless disclosure is required by law.

PAYMENT FOR PARTICIPATION:
I have been told that I will receive $_10/hour____ compensation for my participation in this study. The total study is anticipated to last 1 ½ to 2 hours. If I am unable to complete all six trials due to physical reasons I will be paid for my time at the same rate.

RIGHT TO REFUSE OR WITHDRAW:
I understand that my participation is voluntary and I may refuse to participate, or may discontinue my participation at any time with no adverse consequence. I also understand that the investigator has the right to withdraw me from the study at any time.

INDIVIDUAL TO CONTACT:
If I have any questions about my treatment or research procedures, I understand that I should contact the principal investigator at:

Wayne Latta
Department of MIE, OSE
New Jersey Institute of Technology
University Heights
Newark, NJ 07102-1982
wbl4@njit.edu
610-551-5761

If I have any addition questions about my rights as a research subject, I may contact:

Dawn Hall Apgar, PhD, IRB Chair
New Jersey Institute of Technology
323 Martin Luther King Boulevard
Newark, NJ 07102
(973) 642-7616
dawn.apgar@njit.edu

SIGNATURE OF PARTICIPANT

I have read this entire form, or it has been read to me, and I understand it completely. All of my questions regarding this form or this study have been answered to my complete satisfaction. I agree to participate in this research study.

Participant Name ______________________________

Signature ______________________________

Date ______________________________

APPENDIX B

LEVEL OF BODY DISCOMFORT SURVEY FORM

Participant's Name____

Circle the experimental condition: T1-Low   T1-High   T2-Low   T2-High   T3-Low   T3-High

Circle the level of ache, pain, or discomfort you are experiencing in each of the body regions after completion of this experimental trial.

Fingers/Hand	Nothing at all	Very, very slight	Slight	Moderate	Somewhat severe	Severe	Severe	Very severe		Very, very severe	Unbearable
	0	1	2	3	4	5	6	7	8	9	10
Wrist	Nothing at all	Very, very slight	Slight	Moderate	Somewhat severe	Severe		Very severe		Very, very severe	Maximal
	0	1	2	3	4	5	6	7	8	9	10
Forearm/Elbow	Nothing at all	Very, very slight	Slight	Moderate	Somewhat severe	Severe		Very severe		Very, very severe	Maximal
	0	1	2	3	4	5	6	7	8	9	10
Upper arm	Nothing at all	Very, very slight	Slight	Moderate	Somewhat severe	Severe		Very severe		Very, very severe	Maximal
	0	1	2	3	4	5	6	7	8	9	10
Shoulder	Nothing at all	Very, very slight	Slight	Moderate	Somewhat severe	Severe		Very severe		Very, very severe	Maximal
	0	1	2	3	4	5	6	7	8	9	10
Neck	Nothing at all	Very, very slight	Slight	Moderate	Somewhat severe	Severe		Very severe		Very, very severe	Maximal
	0	1	2	3	4	5	6	7	8	9	10
Upper back	Nothing at all	Very, very slight	Slight	Moderate	Somewhat severe	Severe		Very severe		Very, very severe	Maximal
	0	1	2	3	4	5	6	7	8	9	10
Lower back	Nothing at all	Very, very slight	Slight	Moderate	Somewhat severe	Severe		Very severe		Very, very severe	Maximal
	0	1	2	3	4	5	6	7	8	9	10
Thigh	Nothing at all	Very, very slight	Slight	Moderate	Somewhat severe	Severe		Very severe		Very, very severe	Maximal
	0	1	2	3	4	5	6	7	8	9	10
Foot/Ankle	Nothing at all	Very, very slight	Slight	Moderate	Somewhat severe	Severe		Very severe		Very, very severe	Maximal
	0	1	2	3	4	5	6	7	8	9	10

Rate the tool used in this trial in terms of the following characteristics by circling the appropriate rating number.

	Least favorable								Most favorable	
1. Ease of Use –	1	2	3	4	5	6	7	8	9	10
2. Grip comfort –	1	2	3	4	5	6	7	8	9	10
3. Protection from injury –	1	2	3	4	5	6	7	8	9	10

APPENDIX C

STATISTICAL ANALYSIS OF RESPONSE VARIABLES

Note: Only the statistically significant effects are shown below

Model:

Factor	Type	Levels	Values
Tool	fixed	3	T1, T2, T3
Level	fixed	2	H, L
PRTP	random	16	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16

Analysis of Variance for FINGERS, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tool	2	6.0625	6.0625	3.0313	3.47	0.036
Level	1	0.8438	0.8438	0.8438	0.97	0.329
Tool*Level	2	0.0625	0.0625	0.0313	0.04	0.965
PRTP	15	150.9063	150.9063	10.0604	11.51	0.000
Error	75	65.5313	65.5313	0.8738		
Total	95	223.4063				

S = 0.934746   R-Sq = 70.67%   R-Sq(adj) = 62.85%

Analysis of Variance for UBACK, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tool	2	3.6458	3.6458	1.8229	2.74	0.071
Level	1	0.1667	0.1667	0.1667	0.25	0.618
Tool*Level	2	0.8958	0.8958	0.4479	0.67	0.514
PRTP	15	171.2917	171.2917	11.4194	17.14	0.000
Error	75	49.9583	49.9583	0.6661		
Total	95	225.9583				

S = 0.816156   R-Sq = 77.89%   R-Sq(adj) = 71.99%

Analysis of Variance for Ease of use, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tool	2	19.521	19.521	9.760	6.04	0.004
Level	1	0.375	0.375	0.375	0.23	0.631
Tool*Level	2	0.187	0.187	0.094	0.06	0.944
PRTP	15	182.000	182.000	12.133	7.51	0.000
Error	75	121.250	121.250	1.617		
Total	95	323.333				

S = 1.27148   R-Sq = 62.50%   R-Sq(adj) = 52.50%

Analysis of Variance for Grip comfort, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tool	2	54.250	54.250	27.125	10.26	0.000
Level	1	5.510	5.510	5.510	2.08	0.153
Tool*Level	2	0.083	0.083	0.042	0.02	0.984
PRTP	15	216.240	216.240	14.416	5.45	0.000
Error	75	198.323	198.323	2.644		
Total	95	474.406				

S = 1.62613   R-Sq = 58.20%   R-Sq(adj) = 47.05%

Analysis of Variance for Protection, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tool	2	190.583	190.583	95.292	23.62	0.000
Level	1	0.375	0.375	0.375	0.09	0.761
Tool*Level	2	4.750	4.750	2.375	0.59	0.558
PRTP	15	160.625	160.625	10.708	2.65	0.003
Error	75	302.625	302.625	4.035		
Total	95	658.958				

S = 2.00873   R-Sq = 54.08%   R-Sq(adj) = 41.83%

Analysis of Variance for CARPI RADIALIS BREVIS, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tool	2	203.92	203.92	101.96	6.86	0.002
Level	1	0.88	0.88	0.88	0.06	0.808
Tool*Level	2	1.26	1.26	0.63	0.04	0.958
PRTP	15	10844.05	10844.05	722.94	48.65	0.000
Error	75	1114.56	1114.56	14.86		
Total	95	12164.67				

S = 3.85498   R-Sq = 90.84%   R-Sq(adj) = 88.39%

Analysis of Variance for Ulnar, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tool	2	154.22	154.22	77.11	3.69	0.034
Level	1	2.08	2.08	2.08	0.10	0.754
Tool*Level	2	2.08	2.08	1.04	0.05	0.952
Per	8	583.24	583.24	72.91	3.49	0.004
Error	40	835.80	835.80	20.89		
Total	53	1577.41				

S = 4.57109   R-Sq = 47.01%   R-Sq(adj) = 29.79%

Analysis of Variance for Radial, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tool	2	17.44	17.44	8.72	0.76	0.475
Level	1	62.95	62.95	62.95	5.48	0.024
Tool*Level	2	22.17	22.17	11.08	0.96	0.390
Per	8	3699.02	3699.02	462.38	40.23	0.000
Error	40	459.69	459.69	11.49		
Total	53	4261.26				

S = 3.39000   R-Sq = 89.21%   R-Sq(adj) = 85.71%

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable FINGERS
All Pairwise Comparisons among Levels of Tool
Tool = T1 subtracted from:

```
Tool   Lower   Center     Upper  ---+---------+---------+---------+---
T2    -0.715  -0.1562   0.40227           (----------*----------)
T3    -1.152  -0.5937  -0.03523  (----------*----------)
                                 ---+---------+---------+---------+---
                                  -1.00     -0.50      0.00      0.50
```

```
Tool = T2  subtracted from:

Tool    Lower   Center   Upper   ---+---------+---------+---------+---
T3    -0.9960  -0.4375  0.1210      (----------*----------)
                                 ---+---------+---------+---------+---
                                  -1.00     -0.50      0.00      0.50
```

Tukey Simultaneous Tests
Response Variable FINGERS
All Pairwise Comparisons among Levels of Tool
Tool = T1 subtracted from:

Tool	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
T2	-0.1562	0.2337	-0.669	0.7824
T3	-0.5937	0.2337	-2.541	0.0347

Tool = T2 subtracted from:

Tool	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
T3	-0.4375	0.2337	-1.872	0.1539

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable UBACK
All Pairwise Comparisons among Levels of Tool
Tool = T1 subtracted from:

```
Tool    Lower   Center    Upper    -------+---------+---------+---------
T2    -0.8002  -0.3125  0.17516       (-------------*-------------)
T3    -0.9564  -0.4688  0.01891    (-------------*-------------)
                                   -------+---------+---------+---------
                                        -0.70     -0.35      0.00
```

```
Tool = T2  subtracted from:

Tool    Lower   Center   Upper   -------+---------+---------+---------
T3    -0.6439  -0.1562  0.3314           (-------------*------------)
                                 -------+---------+---------+---------
                                      -0.70     -0.35      0.00
```

Tukey Simultaneous Tests
Response Variable UBACK
All Pairwise Comparisons among Levels of Tool
Tool = T1 subtracted from:

Tool	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
T2	-0.3125	0.2040	-1.532	0.2821
T3	-0.4688	0.2040	-2.297	0.0623

Tool = T2 subtracted from:

Tool	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
T3	-0.1562	0.2040	-0.7658	0.7251

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Ease of use

```
All Pairwise Comparisons among Levels of Tool
Tool = T1  subtracted from:

Tool     Lower     Center    Upper     -+---------+---------+---------+-----
T2     -0.8535   -0.09375   0.6660     (---------*--------)
T3      0.1465    0.90625   1.6660                 (--------*---------)
                                       -+---------+---------+---------+-----
                                     -0.80      0.00      0.80      1.60
```

```
Tool = T2  subtracted from:

Tool    Lower   Center   Upper    -+---------+---------+---------+-----
T3     0.2403   1.000    1.760                   (---------*--------)
                                  -+---------+---------+---------+-----
                                -0.80      0.00      0.80      1.60
```

```
Tukey Simultaneous Tests
Response Variable Ease of use
All Pairwise Comparisons among Levels of Tool
Tool = T1  subtracted from:

       Difference       SE of            Adjusted
Tool     of Means   Difference   T-Value   P-Value
T2       -0.09375       0.3179   -0.2949    0.9532
T3        0.90625       0.3179    2.8510    0.0154
```

```
Tool = T2  subtracted from:

       Difference       SE of            Adjusted
Tool     of Means   Difference   T-Value   P-Value
T3          1.000       0.3179     3.146    0.0066
```

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Grip comfort

```
All Pairwise Comparisons among Levels of Tool
Tool = T1  subtracted from:

Tool    Lower   Center   Upper    ---+---------+---------+---------+---
T2     0.2159   1.188    2.159         (---------*---------)
T3     0.8409   1.813    2.784               (---------*---------)
                                  ---+---------+---------+---------+---
                                    0.0       1.0       2.0       3.0
```

```
Tool = T2  subtracted from:

Tool     Lower   Center   Upper    ---+---------+---------+---------+---
T3     -0.3466   0.6250   1.597    (--------*---------)
                                   ---+---------+---------+---------+---
                                     0.0       1.0       2.0       3.0
```

```
Tukey Simultaneous Tests
Response Variable Grip comfort
All Pairwise Comparisons among Levels of Tool
Tool = T1  subtracted from:
```

Tool	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
T2	1.188	0.4065	2.921	0.0127
T3	1.813	0.4065	4.458	0.0001

Tool = T2 subtracted from:

Tool	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
T3	0.6250	0.4065	1.537	0.2795

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Protection
All Pairwise Comparisons among Levels of Tool
Tool = T1 subtracted from:

```
Tool  Lower   Center  Upper    -+---------+---------+---------+-----
T2    2.175   3.375   4.575                          (-----*-----)
T3    1.112   2.312   3.513                     (-----*-----)
                               -+---------+---------+---------+-----
                             -2.0       0.0       2.0       4.0
```

Tool = T2 subtracted from:

```
Tool   Lower   Center   Upper    -+---------+---------+---------+-----
T3    -2.263  -1.062   0.1377    (-----*-----)
                                 -+---------+---------+---------+-----
                               -2.0       0.0       2.0       4.0
```

Tukey Simultaneous Tests
Response Variable Protection
All Pairwise Comparisons among Levels of Tool
Tool = T1 subtracted from:

Tool	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
T2	3.375	0.5022	6.721	0.0000
T3	2.312	0.5022	4.605	0.0001

Tool = T2 subtracted from:

Tool	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
T3	-1.062	0.5022	-2.116	0.0935

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable CARPI RADIALIS BREVIS
All Pairwise Comparisons among Levels of Tool
Tool = T1 subtracted from:

```
Tool   Lower   Center   Upper   --+---------+---------+---------+----
T2    -2.956  -0.6528  1.651    (--------*---------)
T3     0.410   2.7132  5.017                 (--------*--------)
                                --+---------+---------+---------+----
                               -2.5       0.0       2.5       5.0
```

Tool = T2 subtracted from:

```
Tool  Lower  Center  Upper   --+---------+---------+---------+----
T3    1.063  3.366   5.669                    (--------*---------)
                             --+---------+---------+---------+----
                             -2.5       0.0       2.5       5.0
```

Tukey Simultaneous Tests
Response Variable CARPI RADIALIS BREVIS
All Pairwise Comparisons among Levels of Tool
Tool = T1 subtracted from:

Tool	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
T2	-0.6528	0.9637	-0.6773	0.7774
T3	2.7132	0.9637	2.8152	0.0169

Tool = T2 subtracted from:

Tool	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
T3	3.366	0.9637	3.493	0.0023

Tukey Simultaneous Tests
Response Variable Ulnar

All Pairwise Comparisons among Levels of Level
Level = H subtracted from:

Level	Difference of Means	*SE of* Difference	T-Value	Adjusted P-Value
L	-2.159	0.9226	-2.340	0.0243

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Ulnar
All Pairwise Comparisons among Levels of Tool
Tool = T1 subtracted from:

```
Tool   Lower   Center  Upper    +---------+---------+---------+------
T2    -1.861   1.845   5.551                   (---------*--------)
T3    -5.993  -2.287   1.420         (--------*---------)
                                +---------+---------+---------+------
                              -8.0      -4.0       0.0       4.0
```

Tool = T2 subtracted from:

```
Tool   Lower   Center   Upper     +---------+---------+---------+------
T3    -7.838  -4.132  -0.4254     (---------*--------)
                                  +---------+---------+---------+------
                                -8.0      -4.0       0.0       4.0
```

Tukey Simultaneous Tests
Response Variable Ulnar
All Pairwise Comparisons among Levels of Tool
Tool = T1 subtracted from:

Difference SE of Adjusted

Tool	of Means	Difference	T-Value	P-Value
T2	1.845	1.524	1.211	0.4538
T3	-2.287	1.524	-1.501	0.3014

Tool = T2 subtracted from:

Tool	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
T3	-4.132	1.524	-2.712	0.0260

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Ulnar
All Pairwise Comparisons among Levels of Level
Level = H subtracted from:

```
Level    Lower  Center  Upper  ----+---------+---------+---------+--
L       -2.122  0.3922  2.907  (---------------*---------------)
                               ----+---------+---------+---------+--
                                 -1.5       0.0       1.5       3.0
```

Tukey Simultaneous Tests
Response Variable Ulnar
All Pairwise Comparisons among Levels of Level
Level = H subtracted from:

Level	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
L	0.3922	1.244	0.3153	0.7542

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Radial
All Pairwise Comparisons among Levels of Level
Level = H subtracted from:

```
Level    Lower  Center    Upper  ----+---------+---------+---------+--
L       -4.024  -2.159  -0.2947  (---------------*---------------)
                                 ----+---------+---------+---------+--
                                   -3.6      -2.4      -1.2       0.0
```

Tukey Simultaneous Tests
Response Variable Radial
All Pairwise Comparisons among Levels of Level
Level = H subtracted from:

Level	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
L	-2.159	0.9226	-2.340	0.0243

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