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A biomechanical and psychophysical examination of fastener initiations in automotive assembly.

Joel Aaron Cort
University of Windsor

A BIOMECHANICAL AND PSYCHOPHYSICAL EXAMINATION OF FASTENER INITIATIONS IN AUTOMOTIVE ASSEMBLY

By

Joel Aaron Cort

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by

Joel Aaron Cort

APPROVED BY:

P Keir
School of Kinesiology and Health Science,
York University

L Oriet
Department of Industrial and Manufacturing Systems Engineering

J Jakobi
Department of Kinesiology

J Potvin, Advisor
Department of Kinesiology

W Marino, Chair of Defense
Department of Kinesiology

September 27, 2004

ABSTRACT

A BIOMECHANICAL AND PSYCHOPHYSICAL EXAMINATION OF FASTENER INITIATIONS IN AUTOMOTIVE ASSEMBLY

Joel Aaron Cort
University of Windsor, 2004

The purpose of the current study was to determine acceptable human tolerance limits for a fastener initiation task, which is commonly performed in the automotive industry. A biomechanical and psychophysical methodology was utilized to examine 24 non-skilled female subjects while performing fastener initiation tasks on a simulation device. Three wrist postures (neutral, flexion and extension) in combination with two fastener sizes (large: 10 mm in depth and 20 mm in diameter; small: 5 mm in depth and 10 mm in diameter) were the conditions examined. Fastener initiations per minute, duration of each fastener initiation and the quantity of efforts (individual fastener rotations that comprise each Fastener Initiation) within each fastener initiation were the kinematic measures. Electromyography was also employed to provide data from the muscular activity of the forearm and hands while performing the task. Repeated measures ANOVA with Tukey's significance post hoc test were used to determine any significance within the measured variables ($p<0.05$). Analysis of the data indicated that posture and fastener size variables had significant effects on all of the kinematic data. In fact, subjects were willing to perform the greatest frequency of fastener initiations using the least amount of efforts per fastener initiation in the shortest amount of time. This was based on the values calculated from the kinematic data, which represent values acceptable to 75 percent of the female working population. The recommended acceptable 75 percent values ranged from a high of 7.4 fastener initiations per minute in the F_L/P_N condition and to a low of 6.1 in the F_S/P_E condition. Electromyography data

showed that posture, age and fastener size, although not always in conjunction with each other, contributed to the significance found in the data. Interestingly one muscle in particular, extensor carpi ulnaris, had the highest activity of all muscles regardless of the condition. Thus, this study has provided recommendations on acceptable human tolerances for the task of fastener initiations used in the manufacturing industry. Furthermore, electromyography data provided knowledge about muscle activity within the upper extremity during a low force rotational task.

"All we have to decide is what to do with
the time that is given to us."

<u>LOTR, GTG</u>
J.R.R. Tolkien

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LIST OF ABBREVIATIONS

aEMG: Average EMG amplitude

ANOVA: Analysis of Variance

BB: Biceps Brachii

BR: Brachioradialis

CTS: Carpal Tunnel Syndrome

CMRR: Common Mode Rejection Ratio

COV: Coefficient of Variation

DAC: Deep Anterior Compartment

DIS: Dorsal Interossei

DPC: Deep Posterior Compartment

ECU: Extensor Carpi Ulnaris

Efforts/FI: Efforts per Fastener Initiation

EMG: Electromyography

$F_{L:}$ Large Fastener

$F_{S:}$ Small Fastener

FCR: Flexor Capri Radialis

FCU: Flexor Carpi Ulnaris

FI: Fastener Initiation

FI/min: Fastener Initiations per minute

LMB: Lumbrical

MnPF: Median Power Frequency

MPF: Mean Power Frequency

MUAP: Motor Unit Action Potential

MVE: Maximum Voluntary Exertion

N: Newton

NIOSH: National Institute for Occupational Safety and Health

Nm: Newton Meter

P_N: Neutral Posture

P_F: Flexed Posture

P_E: Extended Posture

PCM: Posterior Compartment Musculature

pkEMG: Peak EMG amplitude

PMI: Palmar Interossei

SAC: Superficial Anterior Compartment

SD: Standard Deviation

SPC: Superficial Posterior Compartment

TLV: Threshold Limit Value

UE: Upper Extremity

UEES: Upper Extremity Evaluation Scale

WMSD: Work Related Musculoskeletal Disorders

Chapter 1

INTRODUCTION

1.1 BACKGROUND

Injuries in the workplace are an important concern as they debilitate workers and are associated with high annual costs to the employer. It has been estimated that employees spend at least one-third of their working lives in hazardous conditions (Kumar, 2001). Workplace research varies in nature from such issues as slips and falls, to low back injuries from lifting, to upper limb injuries from product handling or man-machine interaction. Occupational research endeavors have been sparked by the staggering number of injury claims per annum. In the province of Ontario alone there were 345,879 injury claims filed during 2002 (WSIB, 2003). In the United States (U.S.) the number has been estimated to be as high as 3.9 million per year (Mital *et al.*, 1999). Economists have extrapolated these numbers and have estimated that U.S. workplace injury claims in 1996 cost upward of $121 billion (Mital et al., 1999). This financial responsibility falls on various insurance companies, employers, government agencies and the injured employees themselves. Thus, it can be seen that workplace injuries are a concern for society as a whole.

Many researchers have examined problems within the workplace and consequently, guidelines have been set which attempt to lower the risk of injury. Tools and guidelines have been developed through research collaborations such as the National Institute for Occupational Safety and Health (NIOSH) (NIOSH, 1981), which has set limits for such issues as spinal compression during lifting tasks. As well, the *Strain Index* (Moore and Garg, 1995) and a *Rapid Upper Limb Assessment* (McAtamney and Corlett, 1993) have been developed to contest upper limb injuries. These advances in research have aided ergonomists in limiting exposure to various risk factors, however even after valiant efforts, injuries remain ever present in the workplace.

An examination of workplace injury statistics reveals that there is not an equal distribution of musculoskeletal injuries to each of the body regions. In the last seven years the second most common region of injury on the body was the upper extremity (UE) which consists of fingers, arms, hands and wrists. These areas accounted for 24% of all injury claims, which are second only to the back at 30% of all claims (WSIB, 2003). Upper extremity musculoskeletal injury claims have been linked to risk factors such as poor posture, repetitive motions and substantial forces (Putz-Anderson, 1991; Falkenburg and Schultz, 1993; Józsa and Kannus, 1997; Grieco *et al.*, 1998; Whiting and Zernicke, 1998; Zetterberg and Ofverholm, 1999; Muggleton *et al.*, 1999). Despite considerable efforts to understand and limit the risk factors associated with occupational upper limb disorders, the problem continues to persist, exhibiting very little decline in the number of reported injuries for this body part. Many reasons such as inter-individual differences among workers, continuous product redesign, and inadequate or inappropriate instrumentation during related research, have limited the ability to address all occupational risk factors.

The majority of research dedicated to the upper limb has focused on Carpal Tunnel Syndrome (CTS) (Chiang *et al.*, 1990; Putz-Anderson, 1991; Werner *et al.*, 1997; Józsa and Kannus, 1997; Grieco *et al.*, 1998; Whiting and Zernicke, 1998; Zetterberg and Ofverholm, 1999; Keir and Wells, 1999) however, statistics show that there are several other disorders. This includes disorders such as *Vibration Whitefinger, Cubital Tunnel Syndrome, Guyon's Tunnel Syndromes, Pronator Teres Syndrome, Thoracic Outlet Syndrome, Tendinitis, Tenosynovitis, De Quervain's disease, Trigger Finger* as well as *Medial and Lateral Epicondylitis* (Muggleton *et al.*, 1999). Although, research has been conducted for each of the above, a considerable number of questions remain unanswered.

Due to the large numbers and ranges of injuries within the automotive industry, injuries have been studied extensively through the years. Reports have indicated that, in Ontario alone, 9.6 % of all injury claims were reported by the automotive sector and this was only rivaled by the manufacturing (18.9 %) and service (22.9 %) industries (WSIB, 2003). It must be noted that some companies within the manufacturing sector may too be considered part of the automotive industry (for example, third party suppliers) thereby increasing the magnitude of occupational injury to workers in this field. A very concentrated area of concern has been the upper limb, more specifically the interaction between the human hand and tools needed for task completion. Research such as Potvin et al. (2000) have provided the industry with human tolerance limits or Threshold Limit Values (TLV) for these types of tasks in an attempt to lower injury risk.

However, not all work is completed using tools or automation but, rather, a direct interaction of the worker with the part or object. Injury resulting from this type of interaction should not go unnoticed as they too are associated with a significant number of potential risk factors. Yet, there has been limited research for non-tool assisted tasks and therefore guidelines are virtually non-existent for these activities (Fransson-Hall *et al.*, 1995).

A procedure that occurs both frequently and rapidly within the automotive industry is the application of fasteners for securing parts into place. Most often these fasteners are initiated without the use of tools. There are several reasons why tools are not utilized for these tasks including; location of the part, size of the fastener and precision required to completely tighten the fastener. Most often automotive manufacturers prefer that fasteners are started by human workers, using their hands or fingers for quality reassurance. Through manual application, companies are assured that cross-threading (threads of the fastener are not inline with the accepting threaded end) does not cause damage to either the fastener or part being fastened. Thus, this quality assurance limits mistakes made by human-machine interface avoiding the costs associated with damaged parts and lost production time due to repairing or replacing these parts. Fasteners are frequently applied to the tire wheel-well during assembly. The tire is first placed onto the front or rear axial armature where four to five 'lug nut' fasteners are initiated by the fingers. This is usually a one-limb procedure and motion can be produced by the musculature of the fingers, hands, wrist and forearm. The task may be performed using awkward postures of the upper limb and can occur hundreds of times per shift, extrapolated to thousand of occurrences per work week. As such, this task has been identified as having the potential to cause injury. In order to reduce the risk associated with hand fastening tasks, guidelines for acceptable exposure need to be established.

Given the difficulty associated with data collection for studies involving fasteners used in automotive assembly (valid and reliable instrumentation, workplace distractions and costly assembly line manipulations), the combination of psychophysical and biomechanical research offers an alternative for investigating this type of task.

Psychophysical research is an established area of psychology that is based upon the connection linking a stimulus and its sensation (Gescheider, 1985). Research using the psychophysical theory is based on the perception of the physical stimuli encountered and the resulting psychological sensation following the stimuli (Gescheider, 1985). Utilizing such a method allows for a depiction and, thus, rating of the stimuli based on individual perception and experience with a specific task.

This method, which is based on the human perception of physical task limitations (usually related to force and repetition), offers a reasonably accurate way to estimate the fatigue and discomfort resulting from occupational tasks. Therefore it is quite useful for research involving the workplace (Ciriello *et al.*, 2002). Popularized by Snook and Ciriello, TLVs and guidelines have been set for work tasks such as manual lifting and repetitive hand motions using psychophysics. Without psychophysics, these limits would be quite difficult to assess. More direct measures for examining the effects of physical exposures (eg. intra-muscular strain gauges) are restricted ethically and tend to be costly endeavors (Snook, 1978; Snook and Ciriello, 1991; Snook *et al.*, 1995; Snook *et al.*, 1999; Ciriello *et al.*, 2001; Ciriello *et al.*, 2002). Another recent study proposed TLVs for the hand impacting actions performed during automotive door trim installation using psychophysics (Potvin *et al.*, 2000). This methodology proves to be applicable in a variety of setting and has been used on numerous occasions in determining physical exposure limits.

Electromyography (EMG) has also been used in biomechanical workplace studies to assess the physical demands of various tasks. EMG is based on a combination of biomechanical and physiological phenomena and is used to estimate muscle fatigue, muscle force as well as muscle activation levels during a variety of activities, including occupational tasks. When digitally recorded and filtered, EMG recordings of the electrical/chemical activity (Motor Unit Action Potentials (MUAP)) of a muscle provide estimates of force measurements. Also, recorded MUAP change during fatigued states resulting in shifts in the frequency content of these MUAP from high to lower frequencies (Petrofsky *et al.*, 1982; Solomonow *et al.*, 1990b; De Luca, 1997; Potvin, 1997; Potvin and Bent, 1997). This shift has been widely used to identify potential fatiguing tasks as well as for setting standards in terms of acceptable muscle activation levels.

In summary, the establishment of TLVs for physical exposures offers guidelines for professionals such as ergonomists and engineers to use when evaluating or designing workstations. The role of a TLV is to assist in limiting the potential risk of occupational injury and in order to establish such standards, scientific research on human capabilities needs to be performed. With such a large percentage of all occupational injuries occurring in the upper extremities, it is apparent that tasks involving this region of the body need to be addressed. Currently, TLVs are non-existent for low force, repetitive tasks such as Fastener Initiations (FI) performed in the automotive industry. In order to provide acceptable human tolerance limits for these work activities, quantitative scientific research incorporating practical methodologies such as psychophysics and EMG is essential. A study of this nature would provide ergonomists with an effective tool for the prevention of upper extremities injuries related to FI tasks.

1.2 STATEMENT OF THE PURPOSE

The purpose of the study was to determine acceptable levels of exposure for upper extremity rotations (including the forearm, wrist and fingers) while initiating fasteners for automotive assembly. Utilizing psychophysics, and electromyography methodologies, maximum acceptable initiation frequencies will be determined for three specific wrist postures: neutral, flexed and extended and two fastener sizes (Large: 10 mm in depth and 20 mm in diameter; Small: 5 mm in depth and 10 mm in diameter) during repetitive low force (0.01 Newton meter (Nm)) rotational exertions simulating those observed in industry. The two fastener sizes were chosen to represent the largest and smallest fastener that would be manually manipulated in the automotive industry.

1.3 HYPOTHESES

1. Training sessions will result in consistent and low Coefficient of Variation values pertaining to within-subject variability on the maximum acceptable frequency for fastener initiations.

Subjects will be provided with two hours of training in each of the conditions. In psychophysical based studies involving repetitive UE activities common to the automotive industry, Calder et al. (2004) and Potvin et al. (2004) and (2000) found that subjects displayed consistent Coefficients of Variation, not exceeding 22% and as low as 9% in some cases. This demonstrates that training is effective in familiarizing subjects with the experimental set-up and the actual actions performed throughout the study. Thus, by the end of each subject's total training time it is expected that subject will have a complete understanding of each condition and will be prepared to yield relatively consistent acceptable frequencies during testing.

2. *Psychophysical data will show a statistically significant interaction ($p<0.05$) between UE posture and fastener size. Further Post hoc analysis will show that the highest acceptable frequencies will be exhibited when manipulating the large sized fastener in a neutral wrist posture. This will be greater than when in the flexed and extended wrist postures using either fastener size.*

Non-neutral postures have been identified as a potential risk factor for occupational injuries. These postures may compromise the structures of the involved joint and cause a mechanical disadvantage to the UE, reducing the ability to efficiently perform the desired action (Silverstein *et al.*, 1986; Armstrong *et al.*, 1987; de Zwart *et al.*, 2001). Specific to this study, flexion and extension conditions will limit the contribution of the forearm musculature to supination and pronation, thus decreasing the force of active muscles available to execute the task. In addition, discomfort due to non-neutral postures may negatively affect the subjects perceptions leading to a reduction in the ability to perform the task.

3. *Surface EMG data will show that UE posture will affect EMG amplitudes of recorded muscles. Specifically, variance in muscle electrical activity will occur with changes in postural conditions. When in a Neutral posture, the Extensor Carpi Ulnaris will show highest surface EMG amplitude. For wrist flexion, highest surface EMG amplitudes will be noted for the Brachioradialis and when in extension the Extensor Carpi Ulnaris will show highest surface EMG amplitude.*

Upper extremity postures that deviate from the neutral range change moment arms and muscle lengths thereby effecting force production (Duque *et al.*, 1995). Recorded EMG amplitudes measuring the muscular effort of prime movers have been shown to differ for gripping and hand manipulation tasks when different postures are used. Wrist flexion, extension, pronation and supination have all been identified as reducing the ability of the muscle to produce force (Imrhan, 1991; Duque *et al.*, 1995; Dempsey and Ayoub, 1996; Ljung *et al.*, 1999b; O'Sullivan and Gallwey, 2002; Mogk and Keir, 2003). Thus, in this study, muscles that contribute to maintaining a certain posture as well as producing the necessary force will be affected. This is primarily due to the altered geometry and the need for greater muscle activation in order to produce the same output force.

4. *Reports of discomfort will be greater for flexed posture than for the neutral posture. Also, discomfort will be noted in the distal aspect of the digits for all conditions due to the constant finger-fastener interaction.*

In an unnatural position, the stress experienced in the UE may result in micro-damage, therefore increasing the perceived discomfort. The mechanical stress felt at the finger tips due to constant contact with the fastener is likely to produce feelings of discomfort over the duration of each training/testing session.

Chapter 2

LITERATURE REVIEW

2.1 OCCUPATIONAL MUSCULOSKELETAL INJURIES

Work related musculoskeletal disorders (WMSD) have plagued the workforce for many years affecting workers in both the pre-industrial and post-industrial eras. The 18th century author Ramazinni wrote about '...violent and irregular motions and unnatural postures...' that were causing injury to trades and craftsmen during their working days (Armstrong *et al.*, 1987; Falkenburg and Schultz, 1993). Much time has passed since Ramazinni wrote that statement and the types of processes used in industry have been revolutionized through technological advances. Despite this, WMSD continue to be problematic in occupational settings.

Research indicates that WMSD have been identified among the top ten occupational-related health issues in North American industries (Genaidy *et al.*, 1993). Consequences of WMSD such as human suffering, loss of production and economic drains, have resulted in considerable societal burdens (Genaidy et al., 1993).

Research endeavors pertaining to WMSD have resulted in the identification of specific risk factors associated with several occupational tasks. It is believed that most WMSD are not caused by acute hazardous exposures but rather are the result of constant and repeated events (Putz-Anderson, 1991; Józsa and Kannus, 1997; Whiting and Zernicke, 1998; Muggleton *et al.*, 1999). Repetitive muscular actions can cause micro-trauma to the tissues involved in the movement and can eventually result in an injury (Putz-Anderson, 1991; Miller and Freivalds, 1995; Muggleton *et al.*, 1999).

Many risk factors have been identified in the literature, however the most prominent of these, in no particular order are; *force*, *posture* and *repetition* (Silverstein *et* *al.*, 1986; Goldstein *et al.*, 1987; Silverstein *et al.*, 1987; Armstrong *et al.*, 1987; Chiang *et al.*, 1990; Putz-Anderson, 1991; Falkenburg and Schultz, 1993; Kilbom, 1994a; Kilbom, 1994b; Snook *et al.*, 1995; Fransson-Hall *et al.*, 1995; Abu-Ali *et al.*, 1996; Latko *et al.*, 1997; Klein and Fernandez, 1997; Allen *et al.*, 1997; Zetterberg and Ofverholm, 1999; Ciriello *et al.*, 2002; Mogk and Keir, 2003). The relationship between these three risk factors and WMSD's can be seen in Figure 1. Much debate has ensued over which risk factor weighs greater however, this has proven difficult, as each occupational task has its own unique characteristics.

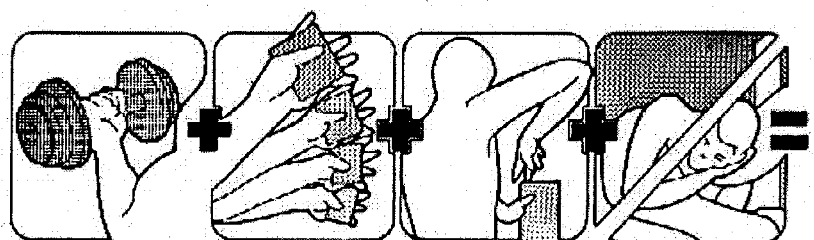

Figure 1. Pictorial representation of WMSD and risk factors (Putz-Anderson, 1991).

Since most tasks performed in the workplace constitute some combination of the three risk factors, researchers have the extremely difficult responsibility of exploring these complex inter-relationships for the purpose of injury prevention (Kumar, 2001).

Silverstein et al. (1987) suggested that certain risk factors may prove to be more hazardous than others. It was found that although forceful exertions were a leading cause of reported hand injuries (specifically CTS and tendinitis), more importantly, repetitive hand motions were shown to play more of a significant overall role. The researchers stated that reoccurring motions compromise the soft tissues and can result in: edema causing nerve compression, inflammation to structures such as tendons affecting force production, and fatigue of the muscle tissues leading to physiological break-down (micro-tears) and eventual injury (Silverstein et al., 1987).

As mentioned, automation in the work environment has offered more efficient methods for production and has, thus, influenced the working environment in terms of human-machine and human-to-human interactions. Furthermore, the influence of ergonomics has led to improved work conditions where some tasks have seen a reduction in associated risk factors. However, even with such advances in the field or ergonomics, problems continue to exist. In fact, Allen et al. (1997) suggested that sometimes, eliminating the traditional risk factors such as force posture and repetition is simply not enough to prevent potential injury inducing tasks. For example, decreasing force levels is usually a positive intervention, however, many low force tasks still involve highly dexterous motions which are also problematic (Allen et al., 1997).

2.2 UPPER EXTREMITY ANATOMY AND PHYSIOLOGY

Structures of the UE are of primary importance during FI rotations. Components of the UE such as muscle tissue, bones, nervous tissue, ligaments and tendons are employed in various orthogonal arrangements and produce forceful yet precise actions. In order to gain a greater understanding of this complex system, a detailed description of the location and function of the specific components is provided below.

2.2.1 Bone Anatomy

The UE which consists of the humeral, forearm, wrist and hand regions consists of a total of 30 bones. Leading from the proximal end is the long humerus bone ending at the elbow joint produced by the articulation of the humerus and the forearm bones, the ulna and radius. Following the ulna and radius to its most distal aspect another articulation is made with the connection to the 8 carpal bones creating the wrist joint. At the distal end of the carpal bone configuration are the 19 bones that make up the hand finalizing the distal aspect of the UE. On various locations on all 30 bones are attachments for muscles, ligaments and tendons which maneuver the appendage to create motion and/or produce force. All information and figures in this section have been adopted from Totora (1999), Totora and Grabowski (1996) and Olson (1996).

2.2.1.1 The Forearm and Wrist

The forearm is made up of two primary long bones: the *ulna* and the *radius*. These bones run in a parallel fashion to each other where in the anatomical position, the ulna is positioned medial to the body and the radius is lateral to the ulna. The bones articulate with each other at both their proximal and distal ends. In addition, the proximal ends of ulna and radius articulate with the distal end of the *humerus* and form the elbow joint (Figure 2).

The articulation of the humerus and ulna provides flexion and extension at the elbow. Also, the proximal articulation of the ulna and radius partially contributes to supination and pronation (internal rotation) of the forearm. These two motions are required during FIs.

Wrist flexion and extension is a result of individual articulations between carpals as well as between the proximal carpal bones and the ulna and radius. Joints are formed between the distal aspect of the radius and the *scaphoid* and *lunate* bones. The ulna is also connected to the lunate as well as the *triquetral* bone. Together, these unions form the wrist joint and are responsible for flexion and extension as well as radial and ulnar deviation of the wrist (Figure 3). In addition, both the distal and proximal articulations between the ulna and radius produce supination and pronation (internal rotation) of the forearm. In order to structurally complete all of these motions, dense fibrous tissue, known as ligaments, connect each of the bones and assist in maintaining the integrity and stability of each joint.

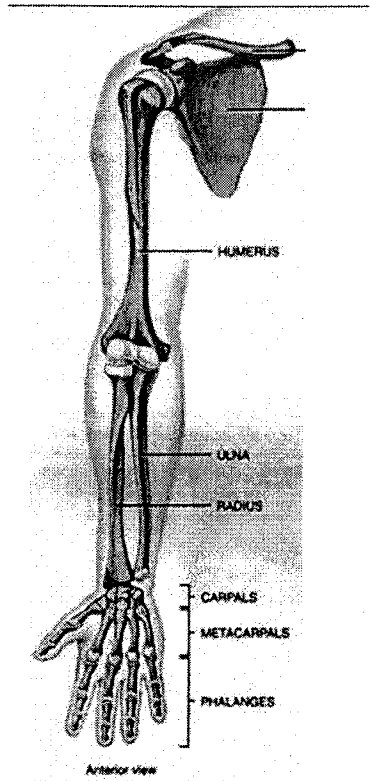

Figure 2. Bones of the upper extremity (Tortora, 1999).

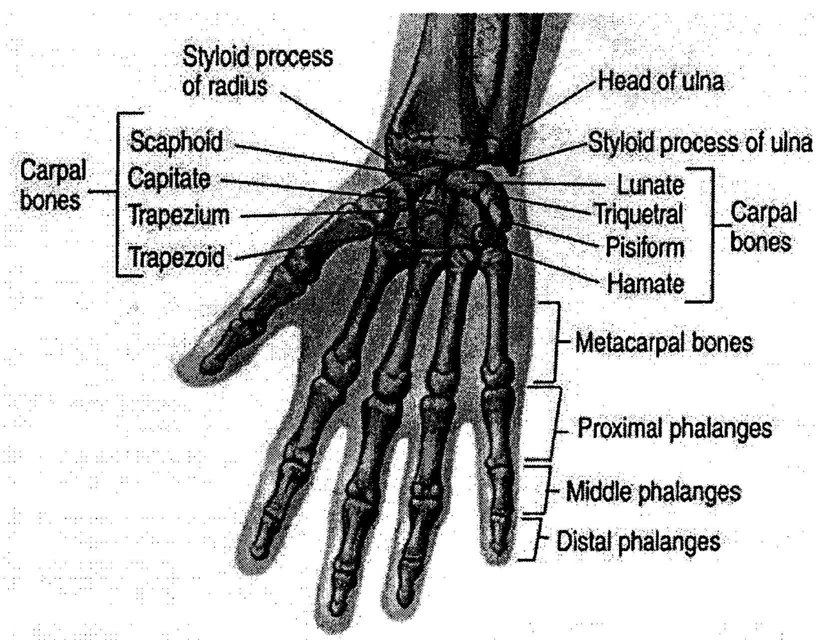

Figure 3. Bones of the wrist and hand (Olson, 1996).

2.2.1.2 The Human Hand

The human hand is known as the most complex structure of the body and is comprised of 8 short bones (wrist), 4 sets of 4 long bones (fingers) and one set of 3 long bones (thumb) for a total of 27 bones (Figure 3).

The proximal aspect of the hand (palm), consists of 8 *Carpal* bones. The names of these bones listed from proximal to distal and lateral to medial are: *scaphoid, lunate, triquetral, pisiform, trapezium, trapezoid, capitate* and *hamate* (Figure 3). These bones articulate with each other to assist in unique movements such as flexion, extension and circumduction of all digits as well as opposition of the digits.

Leading from the carpal bones are 5 separate connections of long bones that make up the digits (fingers). This includes the *index* (2^{nd}), *middle* (3^{rd}), *ring* (4^{th}) and *little* (5^{th}) digits. From proximal to distal these four bones are entitled: *metacarpals, proximal phalanges, middle phalanges* and finally *distal phalanges* (Figure 3). The 1^{st}, digit also known as the thumb, is unique to the other four digits as it is comprised of one less bone. Instead, the 1^{st} digit has a metacarpal and only a proximal and distal phalange.

The articulations made between the metacarpal bones and the phalanges allow for flexion and extension of the digits. More importantly, the vast number of bones within the hand allow for fine and precise motions of the hand. These movements facilitate delicate tasks, such as threading a needle and keyboard typing, to forceful grasping of tools and hand impacts when securing an object in place. During many automotive assembly tasks, the hand often serves as a tool where it is in direct contact with an object or part. For example, during fastener installation, the hand is responsible for securing the fastener to the automobile.

2.2.2 Muscles of the Upper Extremity

Muscles of the UE which produce motion necessary for FIs in automotive assembly will be described in this section. All muscles introduced below have tendon attachments on the bones discussed in Section 2.2.1. These muscles attempt to shorten, which lengthen the tendons to create a pulling action on the bones. It is this pulling action that causes motion of specific body parts.

2.2.2.1 Humeral Musculature

The muscles of the humeral area of the UE consist of the *biceps brachii* (BB) muscle on the anterior aspect of the arm. The role of this muscle is to produce flexion and supination of the forearm. In addition to the BB, the *brachioradialis* (BR) is located on the anterior aspect of the UE and spans from the humerus, across the elbow joint and onto the forearm and can also be thought of as part of the forearm musculature. The BR causes flexion at the elbow and both supination and pronation of the forearm. Along with these two anteriorly located muscles is the *brachialis,* which provides flexion of the forearm at the elbow joint. Antagonist to the aforementioned muscles is the *triceps brachii.* This large muscle is located on the posterior aspect of the humerus, and contributes to extension of the forearm at the elbow joint. All muscles in the humeral area of the UE can be viewed in Figure 4.

2.2.2.2 Forearm Musculature

The muscles of the forearm have been classified into two different groups based on their location and function. The two groups are known as the *anterior compartment musculature,* located on the anterior portion of the forearm and functioning as the flexors and the *posterior compartment musculature* (PCM), located on the posterior aspect of the forearm which provides extension. Based on muscle arrangement, these compartments are further categorized into superficial and deep. Thus the anterior compartment or the flexors have both a *superficial anterior compartment* (SAC) and a *deep anterior compartment* (DAC) *(Vidacek et al., 1993).* Similarly, the posterior compartment or the extensors have a *superficial posterior compartment* (SPC) and a *deep posterior compartment* (DPC) (Figure 4 (a) & (b)).

There are four muscles that comprise the SAC. The *flexor carpi radialis* (FCR) which flexes and abducts the hand at the wrist. Flexion of the hand at the wrist is also a responsibility of the *palmaris longus.* Hand adduction, also known as ulnar deviation, and flexion occurring at the wrist are produced by the *flexor carpi ulnaris* (FCU). The *flexor digitorum superficialis* has a number of roles including flexion of the middle phalanges as well as the hand at the wrist (Figure 4 (a)). Two muscles make up the flexor or DAC of the forearms. Flexion of the thumb is accomplished by the *flexor pollicis longus.* Finally, the last muscle of the DAC, *flexor digitorum profundus*, has the responsibility of flexing the distal aspect of each digit as well as assisting in flexion of the hand at the wrist.

The PCM contains 9 muscles, five in the SPC and four in the DPC. Those within the SPC include the *extensor capri radialis longus* and the *extensor carpi radialis brevis*, both of which extend and adduct the hand at the wrist. As well, the *extensor digitorum acts to* extend the digits and the hand at the wrist. Another muscle, the *extensor digiti minimi* provides extension of the 5^{th} digit and assists extension of the hand at the wrist. Lastly, the *extensor carpi ulnaris* (ECU) is responsible for extending and adducting (ulnar deviation) the hand at the wrist (Figure 4 (b)).

Within the DPC, abduction and extension of the thumb and radial deviation is completed by the *abductor pollicis longus.* The *extensor pollicis brevis* provides assistance for extension of the thumb and hand at the wrist. The *extensor pollicis longus* also aids thumb extension and radial deviation of the hand at the wrist. Finally, extension of the index digit and the hand occurs through the *extensor indicis* (Figure 4 (b)).

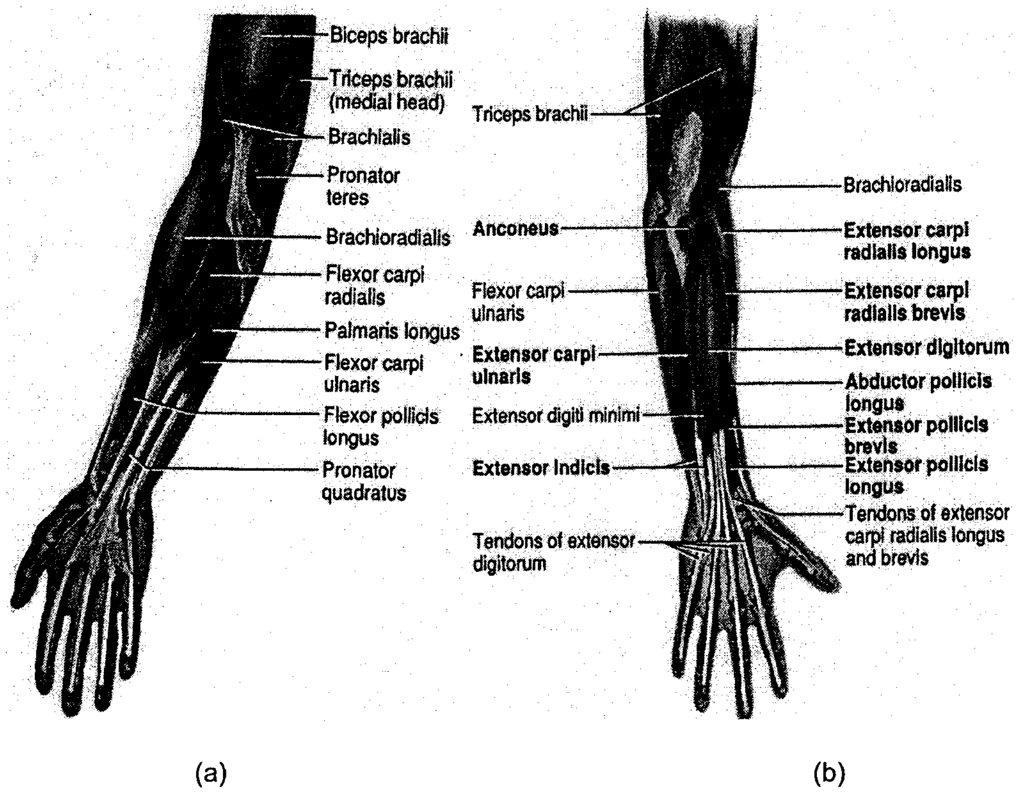

Figure 4. Forearm muscles: a) the anterior view of the forearm muscles, b) posterior view of the muscles of the forearm (Saladin, 1998).

2.2.2.3 Hand Musculature

Muscles of the hand are not known for large force production but rather accurate and complex movements. It is these muscles that allow for the precision needed during FIs. There are ten hand muscles and they are categorized into three distinct groups based on location: *thenar, hypothenar and intermediate.*

The Thenar group consists of four muscles located on the radial side of the hand. The *abductor pollicis brevis* muscle is responsible for abducting the thumb. Opposition between the thumb and 5th digit is provided by the *opponens pollicis*. Flexion of the thumb and the digits is accomplished by the *flexor pollicis brevis*. The *adductor pollicis* aids in thumb adduction (Figure 5). The hypothenar muscle group, made up of 3 muscles, can be found on the ulnar side of the hand. It includes the *abductor digiti minimi*

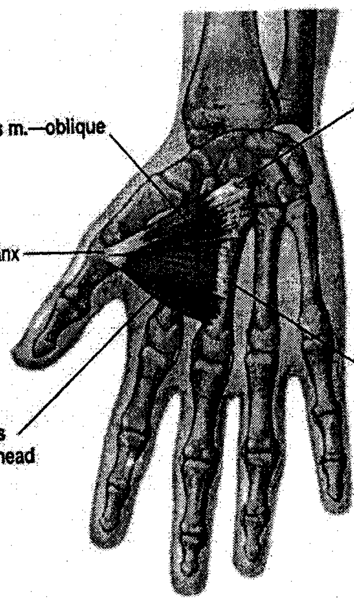

Figure 5. Thenar muscles of the hand (Olson, 1996).

and the *flexor digiti minimi brevis* which both serve to flex and abduct the 5th digit. The *opponens digiti minimi* allows the 5th digit to oppose the thumb.

The intermediate muscle is comprised of three muscles identified as: *lumbricals* (LMB), *palmar interossei* (PMI) and the *dorsal interossei* (DIS). These are situated in the middle portion of the palm. The LMB provides both digit flexion and extension. The PMI adducts the digits and also assists with flexion of the digits. The DIS assists the PMI and the LMB in adduction, flexion and extension of the digits.

2.2.3 Nervous System

Within the UE, there is a large network of nerve tissue supplying electrical impulses to musculoskeletal tissues. The nerve network is vital to function of the UE and thus if damaged, impairment to normal function may result.

The nerves which are important to identify for this study are the *median*, *ulnar* and *radial nerves*. The median nerve is located intermediate to the ulna and radius and its distal aspect travels through the wrist via the carpal tunnel. The median nerve innervates all digits except the 5th and one half of the 4th. It is the carpal tunnel that the median nerve travel through that gives rise to such disorders as CTS as the nerve becomes pinched as the tunnels diameter becomes constricted. The *radial nerve* moves along the lateral portion of the UE innervating this region and the posterior aspect of 1st and 2nd digits. The radial nerve may be affected by such disorders as Lateral Epicondylitis. In addition, the *ulnar nerve* travels down the medial aspect of the UE innervating tissues of this region as well as the 4th and 5th digits of the hand and is associated with Medial Epicondylitis syndrome.

2.3 RISK FACTORS FOR UPPER EXTREMITY DISORDERS

Upper Extremity occupational disorders rank second only to back disorders in all non–fatal work related injuries (WSIB, 2003). This may not be all that surprising as almost all tasks within industry require the use of the UE. As noted previously, risk factors for UE WMSD's include posture, force and repetition. Despite the considerable research efforts to identify the three aforementioned risk factors of occupational related injuries, relatively little work has been done to establish acceptable limits for UE activities (Schoenmarklin *et al.*, 1994).

A commonly cited study by Silverstein et al. (1987) examined UE tasks within occupational settings to address the risk factors associated with CTS. Silverstein et al. (1987) showed that when high forces were combined with very repetitive tasks, the risk of injury increased. However, when assessed individually, repetition appeared to be a greater risk factor, statistically, than force (Silverstein *et al.*, 1987). In another study on UE WMSD it was concluded that the combination of both high repetition and high force was substantially worse than either variable by itself (Silverstein *et al.*, 1986). Given the evidence to suggest that jobs performed at high frequencies are in fact risky, it is important to address this issue through continued research endeavours and in practical terms, during the design of jobs. This notion is further strengthened by the research of Armstrong et al. (1987) who found that jobs containing high force and high repetition had odds ratios of 30 times greater than that of low force and low repetition tasks.

UE postures that deviate from a neutral structural alignment may bring about mechanical disadvantages which can decrease force production, impinge on the nerves and/or place stress on the bones due to misalignment. A number of researchers have concluded that certain postures of the UE, in particular the wrist, compromise the integrity of the internal environment of the involved structures (Goldstein *et al.*, 1987; Chatterjee, 1992; Moore and Garg, 1995; Hagg *et al.*, 1997; Klein and Fernandez, 1997; Mogk and Keir, 2003). Specifically, Klein and Fernandez (1997) examined the acceptable frequency for pinch actions and found that the maximum acceptable frequency when using a neutral wrist posture was unattainable when subjects wrists were flexed. Goldstein et al. (1987) reported an increase in shear forces of the wrist tendons during flexion and extension compared to a neutral posture. Furthermore, an EMG evaluation of UE muscle activity showed that when placed in a flexed wrist posture, electrical activity of the forearm musculature was greater than the acceptable limits recommended by Jonsson (1982), even in the absence of force production (Mogk and Keir, 2003).

The above evidence provides impetus for limiting exposure to harmful postures, force exertions and repetitive motions of the UE during occupational tasks. These risk factors must be considered individually, as well as in conjunction with one another during the design and redesign of workplace activities.

2.4 WORK RELATED MUSCULOSKELTAL DISORDERS OF THE UPPER EXTREMITY

A number of WMSD have been identified as problematic in occupational settings. The risk factors discussed in Section 2.3 are believed to be the main contributors to disorders of the nerve, bone, muscle, ligament and tendon tissues. According to Putz-Anderson (1991), WMSD's can be placed into simplified categories: tendon and nerve disorders. To gain a greater understanding of the most commonly reported occupational disorders, a brief description will be provided below.

2.4.1 Upper Extremity Tendon Disorders

The WMSD's of the tendon are associated with motion around joints. Constant contact or friction with rigid boney structures can cause micro-trauma of the tissue (Putz-Anderson, 1991; Józsa and Kannus, 1997). Overtime these micro-traumatic experiences summate and cause the tissue to display symptoms of pain, discomfort, inflammation and tenderness (Putz-Anderson, 1991; Muggleton *et al.*, 1999). More specifically, lateral and medial epicondylitis are commonly diagnosed occupational injuries of this nature.

Medial or lateral epicondylitis has been described as an inflammation or irritation at the elbow joint of the ulnar or radial nerves (Silverstein *et al.*, 1987; Putz-Anderson, 1991; Józsa and Kannus, 1997; Whiting and Zernicke, 1998; Muggleton *et al.*, 1999). Forceful and repetitive supination, pronation, flexion and extension motions of the forearm and hands have been identified as risk factors for these two disorders. Micro-trauma can occur to the tendons that perform these motions as they are in constant contact with the humeral epicondyles (both medial and lateral). Eventually, this can lead to cumulative trauma to the tissue (Putz-Anderson, 1991; Józsa and Kannus, 1997; Whiting and Zernicke, 1998; Muggleton *et al.*, 1999; Ljung *et al.*, 1999a). Symptoms of epicondylitis include pain, numbness and discomfort in the forearms and hands.

2.4.2 Upper Extremity Nerve Tissue Disorders

Nerve disorders usually result from mechanical stress, most often from nerve compression when passing through a rigid structure. Most often these rigid structures (bones) become problematic by either decreasing the size of the canal that the nerve passes through or actually impinging on the nerve itself (Putz-Anderson, 1991; Józsa and Kannus, 1997; Whiting and Zernicke, 1998; Zetterberg and Ofverholm, 1999; Muggleton *et al.*, 1999). The most commonly known and researched UE nerve tissue disorder is Carpal Tunnel Syndrome (CTS). CTS results from decreased space within the carpal tunnel where the median nerve passes (Figure 6). Poor postures, high forces

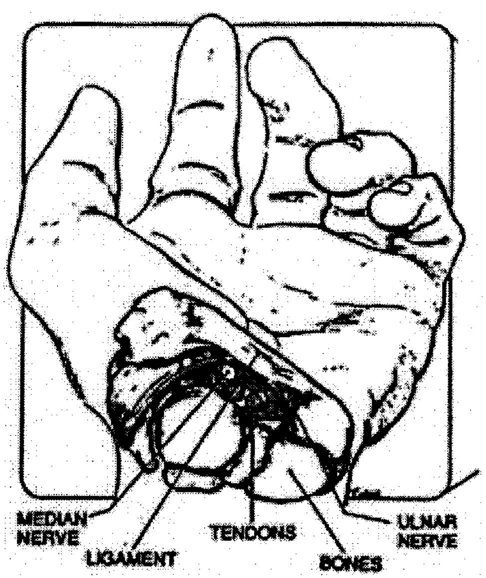

Figure 6. A diagram of the Carpal Tunnel with the tendons, ligaments, nerves and vascular tissues that passes through (Putz-Anderson, 1991)

and repetitive movements have been associated with CTS (Silverstein *et al.*, 1986; Silverstein *et al.*, 1987; Armstrong *et al.*, 1987; Chiang *et al.*, 1990; Putz-Anderson, 1991; Schoenmarklin *et al.*, 1994; Zetterberg and Ofverholm, 1999; Muggleton *et al.*, 1999). Commonly reported symptoms of CTS are pain in the wrist and hand, numbness and tingling of the digits as well as decreases in force production and range of hand motion (Putz-Anderson, 1991; Whiting and Zernicke, 1998; Muggleton *et al.*, 1999).

2.5 PSYCHOPHYSICAL RESEARCH

The science known as *psychophysics* is a sub-discipline of psychology that deals with human perception through a connection between cognitive sensation and physical stimuli (Gescheider, 1985). This branch of psychology is based on the assumption that there is an association between a physical stimulus and the human perception (processed cognitively) of that stimulus. It is believed that humans are able to determine physical differences based on this connection. Known as the *Principle of Nomination*, a constant physical stimulation will elicit the exact same cognitive impression, thus not changing human perception with unchanged stimulations (Gescheider, 1985). In order to yield a cognitive response from the system, stimulations must exceed the threshold to produce an awareness of that stimulus. An applied example of this theory is the human awareness of stimulation to cutaneous touch and pressure receptors of the skin following a variety of force applications. An elapsed threshold can result from a deviation in the intensity, quality, extension or duration of a stimulus (Gescheider, 1985). Once the threshold is broken, perception of the stimulus changes and an alteration within the physical environment occurs to evoke a response. Researchers such as Gescheider (1985) have stated that, due to the linear connection between the physical and mental worlds, psychophysics is a valuable tool that can be used to understand the human sensory experience.

Psychophysics has been used to determine acceptable human limits for such tasks as manual material handling (including lifting, lowering, pushing, pulling and carrying) and hand manipulation activities (Snook and Irvine, 1967; Snook *et al.*, 1970; Snook, 1978; Jiang *et al.*, 1986a; Jiang *et al.*, 1986b; Snook and Ciriello, 1991;

Fernandez *et al.*, 1991; Dahalan and Fernandez, 1993; Kim and Fernandez, 1993; Davis and Fernandez, 1994; Snook *et al.*, 1995; Marley and Fernandez, 1995; Snook *et al.*, 1997; Snook *et al.*, 1999; Ayoub and Dempsey, 1999; Potvin *et al.*, 2000; Ciriello *et al.*, 2001; Ciriello *et al.*, 2002). According to Gescheider (1985) one of the earliest accounts of the use of psychophysics in human research was in the early 19th century by a German physiologist, E.H. Weber. Weber used this method to determine perceptions of different handled weight. Since this work, researchers such as Snook and Ciriello have completed many well respected studies and have developed guidelines used by ergonomists and occupational biomechanists world wide (Snook, 1978; Snook and Ciriello, 1991; Snook *et al.*, 1995; Snook *et al.*, 1999; Ciriello *et al.*, 2001; Ciriello *et al.*, 2002).

Most notably Snook, in association with the Liberty Mutual Research Centre, used psychophysics to develop acceptable human tolerance levels during manual material handling tasks. Using the equation derived from Stevens (Stevens, 1960), where S (strength of sensation), I (intensity of physical stimuli) and k (constant of measurement used) are directly related through $S = kI^n$. Snook was able to use the linear relationship (log-log determined and power law obeyed) produced through this equation to gain a better understanding of the link between muscular effort and force produced (Snook and Irvine, 1967; Snook *et al.*, 1970; Snook, 1978; Snook, 1985; Snook and Ciriello, 1991; Snook *et al.*, 1995; Snook *et al.*, 1997; Snook *et al.*, 1999). While controlling variables such as posture and frequency, subjects were instructed to monitor their own perception of exertion during lifting (high intensity of work without strain, unusual fatigue or feelings of weakness). Subjects took part in training sessions in order to get acquainted with the instrumentation, working environment and most importantly the task being performed prior to the collection of any data. While working on an incentive basis in both training and testing sessions, subjects were able to choose and adjust the quantity of weight lifted, frequency of the task or the force applied based on their psychophysical perception (Snook, 1978). Using results from a number of studies conducted by Snook and colleges at the Liberty Mutual Research Center, maximum acceptable exposure levels for manual handling tasks were determined. Based on these projects Snook reported in 1978 that the risk of injury to the low back was three times higher for tasks that were acceptable to less than 75 percent of the working population. Therefore, Snook recommended that in order to limit the risk of occupational injury, manual material handling tasks should be designed to accommodate 75 percent of the population.

The Snook studies have popularized the psychophysical methodology among occupational research. Using this approach, all but one variable is controlled by the investigators while subjects adjust that one variable in accordance with their perception of muscular effort and discomfort. For the current study the variable that was controlled by the subject was frequency. More recently, this method has been used to gain knowledge about the UE. Psychophysics is an attractive tool for UE research as the UE is a complex structure which proves difficult to measure with direct instrumentation (strain gauges, goniometers etc), especially in an occupational settings.

In order to determine acceptable repetitive wrist flexion and extension Snook (1995), controlled repetition, forearm posture, grip type and type of motion used (flexion and extension) while allowing the subjects to control the amount of force exerted. Subjects could exert the most resistance (combined mean 4.10 Nm) when conditions involved wrist flexion in combination with a power grip (contact with the entire hand) and a frequency of five wrist motions per minute during a two day per week exposure (Snook *et al.*, 1995). Conversely, when wrist extension with a power grip and a rate of 20/min was required subjects exhibited the lowest acceptable torque values at 1.5 Nm (combined subject mean) (Snook *et al.*, 1995). In an extension of the same study, Snook et al. (1995) determined acceptable wrist flexions using a fixed repetition rate of 15/min, as opposed to varying the rate as was done in the first study. Subjects took part in five days per week of exposure for a total of 23 days. Results showed acceptable limits of no more than 2.29 Nm of muscular resistance was acceptable, which was approximately 30% of the subject's maximum isometric force (Snook *et al.*, 1995). The authors concluded that values obtained in this study are the best estimate of human tolerance to these specific conditions (Snook *et al.*, 1995).

Another research endeavor led by Snook in 1999 also used psychophysics to determine acceptable forces for wrist extension motions using a pinch grip. Repetition rates of 15, 20 and 25/min were studied and subjects were asked to simulate a normal work week by participating 7 hours a day, five days a week, for total of four weeks. The acceptable force decreased with exposure to higher repetition. Specifically there was a 23% drop in acceptable torque (Nm) when repetition increased from 15 to 25/min (Snook *et al.*, 1999). Snook et al. (1999) suggests that maximum acceptable rotational exertions (Nm) of the UE (Werner *et al.*, 1997) are greater for flexion postures than extension and using a power grip rather than a pinch grip also permits higher torques (Snook *et al.*, 1999). This information has been used to steer the development of guidelines for UE tasks within occupational settings.

Ciriello et al. (2002) and Potvin et al. (2000) have also used psychophysics to determine acceptable exposure limits for UE tasks. Ciriello et al. (2002) investigated acceptable limits for repetitive UE rotations of the hand and forearm while operating powered screw guns. Findings from this study mirrored that of the Snook (Snook *et al.*, 1995; Snook *et al.*, 1999) studies discussed previously. Acceptable tolerance levels to rotational forces were below 0.7 Nm for a screw driving task, and hand grip tasks (15, 20, and 25 per minute) involving ulnar deviation had a threshold of 5 Nm.

Potvin et al. (2000) utilized psychophysics to determine acceptable hand impact exposures during the assembly of door panels in an automobile. Due to quality concerns, workers are required to use their hands rather than tools in order to secure the interior trim panel of the door. The study investigated acceptable limits during a 5 impacts/minute condition and also examined limits during a varying repetition rate of 2 and 8/min. Subjects controlled the amount of resistance (pounds per square inch) impacted against and acceptable forces and impulses were found to be frequency dependent. Tasks in which the worker is required to use his/her body as a tool have been associated with negative consequences to the worker and thus it is imperative that exposure limits are identified and employed in task design.

In addition to the Potvin and Ciriello, studies utilizing the psychophysical methodology have been completed on industrial tasks involving the use of tools. In particular, studies by Armstrong, Punnett, and Ketner (1999), Kim and Fernandez (1993),Davis and Fernandez (1994), and Marley and Fernandez (1995) were initiated to deal with injury problems associated with human-tool interaction. The study by Armstrong et al. (1989) was the first to validate this methodology for activities requiring hand tools by correlating subjective measures of such variables as tools mass and handle size to the actual objective measures. In further studies, psychophysics has been used to examine repetitious drilling activities with the use of a hand tools and set maximum acceptable frequencies for these actions when performed in different postures (Davis and Fernandez, 1994; Marley and Fernandez, 1995) Furthermore, limits were set for the same activity while varying the force requirements (Kim and Fernandez, 1993).

Psychophysics can provide reasonable estimates of human tolerance to physical exposures in occupational settings. Following training in specific occupational tasks, within-subject variability was low, solidifying the reliability of this type of method. Potvin et al. (2000) reported average Coefficients of Variation (COV) for dependent variables to be no greater than 22% and as low 9% in a hand impact study. In addition, Cort et al. (2004) found that during manual electrical coupling tasks the average CVs did not exceed 10% for each of the dependent measures. Furthermore, in recent work by Calder et al. (2004), subjects performing hose insertion tasks common to automotive assembly did not have CVs larger than 13% for any dependent variable. These results confirm that psychophysics is a reliable method of data collection, making it an attractive approach for occupational research endeavours.

Psychophysics is based primarily on subjective measurements, which can be both positive and negative. While there is potential for bias in subjective measure, the ability to collect data using a large, diverse sample of the population serves to counterbalance this bias. Thus, data provided using this methodology has the benefit of involving actual subjects and their preferences, as opposed to establishing guidelines based on professional observation or some other technique (Moore and Garg, 1995). In conclusion, psychophysics has been well accepted in the research community as providing realistic estimations of human physical exertion and is a practical means of determining safe work guidelines (Putz-Anderson and Grant, 1995).

2.6 ELECTROMYOGRAPHY

Electromyography (EMG) is a recording of motor unit action potentials (Inbar *et al.*, 1987), an electrical/chemical signal provided by the nervous system that signals muscle tissue to contract. The use of surface EMG in kinesiology-related research has been designated primarily to estimating activation levels of muscles for the purpose of approximating individual muscle forces, and to quantify muscular fatigue levels (Petrofsky *et al.*, 1982; Winter, 1990; De Luca, 1997; Potvin, 1997; Potvin and Bent, 1997). Much controversy exists regarding the validity of using EMG to quantify both muscular fatigue and force, given the fact that factors such as electrode placement and digital filtering techniques can effect the consistency of results (De Luca, 1997). Despite this, it has been consistently cited in the literature and continues to serve as a useful tool in the assessment of muscle function.

The use of EMG as a method to estimate muscular force is an attractive means to investigators as direct measurements using such instrumentation as a strain gauge is unacceptable as they are extremely invasive and such foreign objects may have the potential to alter human movement (Solomonow *et al.*, 1990a; Acierno *et al.*, 1997; De Luca, 1997). Thus, recordings of MUAP's recorded by EMG have been thought to give insight into the tension generated by muscle tissue. Yet, this is not a simple phenomenon and many physiological and biomechanical variables need to be considered for results to be valid. Variables such as muscle length, cross-section area of muscle, velocity of muscle movement, motor unit recruitment and discharge rate need to be measured and incorporated when using EMG to predict muscle force generated (Solomonow *et al.*, 1990a; Solomonow *et al.*, 1990b; Acierno *et al.*, 1997; De Luca, 1997). In addition, muscle fiber composition of Type I and Type II fibers has also been shown to affect the non-linear relationship between force and EMG (Solomonow *et al.*, 1990a; Solomonow *et al.*, 1990b; Acierno *et al.*, 1997; De Luca, 1997; Onishi *et al.*, 2000). Due to the difficulties it has been reported that the best predictor for force based on EMG comes from muscles exerting force isometrically (Solomonow *et al.*, 1990a; Solomonow *et al.*, 1990b; Acierno *et al.*, 1997; De Luca, 1997). Yet, with a growing body of knowledge about the EMG-force relationship the ability of EMG to measure dynamic muscle activity has improved, thereby strengthening the predictive power of this relationship. In particular, Marras and Sommerich (1991) developed a model to aid in the prediction of force from EMG collected during dynamic activity.

$$Force = gain \times \frac{EMG}{EMG_{\max}} \times mvelocity \times CSA \times mlength$$

where: gain = maximum force per unit of area
EMG = recorded
EMG_{max} = obtained MVE
mvelocity = velocity of muscle during the motion
CSA = muscle fibers in a cross sectional area
mlength = total anthropometric length

The relationship between EMG and fatigue is usually addressed with respect to the frequency content and shape of the signals recorded by electrodes. More specifically, frequency content analyses are used to examine spectral shifts in signal power from higher to lower frequencies during the onset of isometrically fatigued muscles. This shift is traced through measurements of the Mean or Median Power Frequency (MnPF and MPF, respectively) of the EMG signal (Petrofsky *et al.*, 1982; De Luca, 1997; Potvin and Bent, 1997). More recently, it has been shown that the shifts in MnPF during isometric contractions, can also be seen during dynamic muscular contractions (Potvin and Bent, 1997). The analysis of dynamic muscular contractions allows for a more realistic analysis of human movement.

Chapter 3

METHODS

The current chapter is dedicated to the methodology that was employed for this study. The study design, subjects, instrumentation, protocol and data analysis is described.

Prior to any involvement with the project, subjects were asked to read and sign a written consent form (Appendix A). Upon completion of their participation, subjects were given monetary compensation. All aspects of this study have been reviewed and approved by the University of Windsor Research Ethics Board (Appendix A).

3.1 STUDY DESIGN

The current study used psychophysics to identify a series of TLVs for UE rotations during the initiation of a fastener to an object on an automotive assembly line. Subjects were asked to replicate the motions identified in the workplace using a device constructed and positioned within a laboratory setting. Since workers in the automotive industry perform this task using gloves, subjects were required to wear an industry standard glove on the active hand (Sure Knit, cotton/polyester blend with seamless knit, Superior Glove Works Ltd.) and to use their dominant hand to complete each FI. One FI was identified as the sum of 720 degrees of angular rotation of the fastener. The degree of angular rotation that composes a FI was determined qualitatively by the experimenters through video and assembly line observation of the task in the automotive industry. Each FI consisted of a discrete number of efforts providing the movement of the fastener to end goal of 720 degrees of rotation. Each subject determined their acceptable frequency of FI's that can be completed per minute. Subjects were instructed to complete the task in a manner that does not cause discomfort, pain or numbness in any area of the UE. However, subjects were encouraged to elicit a work intensity (repetition and velocity) that would be reasonable for workplace tasks. Instructions were provided for participants prior to each session to ensure that data collected closely simulated what would be seen in an occupational setting (Instructions have been adopted from previous studies and can be reviewed in Appendix B) (Snook, 1978; Snook and Ciriello, 1991; Snook *et al.*, 1995; Snook *et al.*, 1999; Ciriello *et al.*, 2002).

The independent variables in this study can be viewed in Figure 7. The independent variables in this study were *Fastener Size, Wrist Posture* and *Age.*

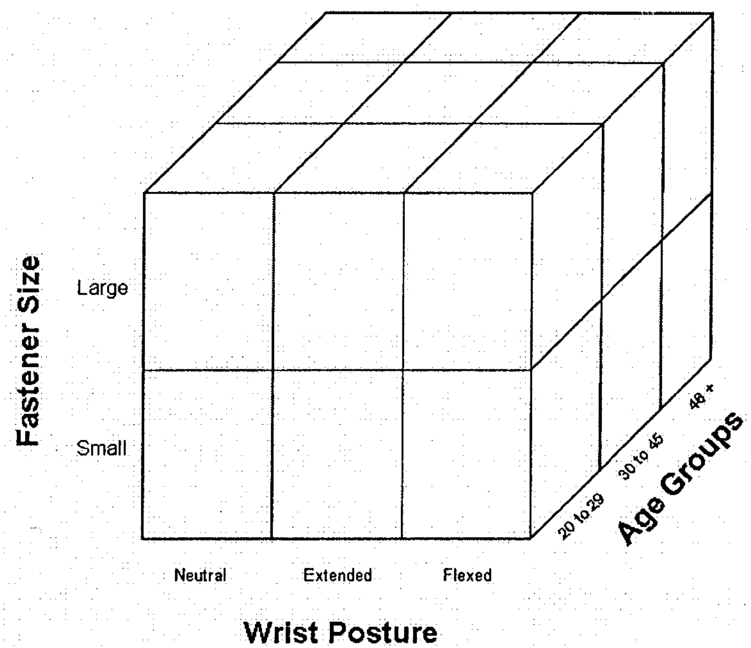

Figure 7. Independent variable matrix for the current study.

Subjects were exposed to two separate fastener sizes with contact surface dimensions as follows: 10mm in depth and 20 mm in diameter (Large, S_L; 5 mm in depth and 9 mm in diameter (Small, S_S) (Figure 8).

Also, subjects performed the tasks with 3 wrist postures: 1) wrist neutral and fastener horizontal (Neutral Posture, P_N), 2) wrist flexed and fastener vertical, 90

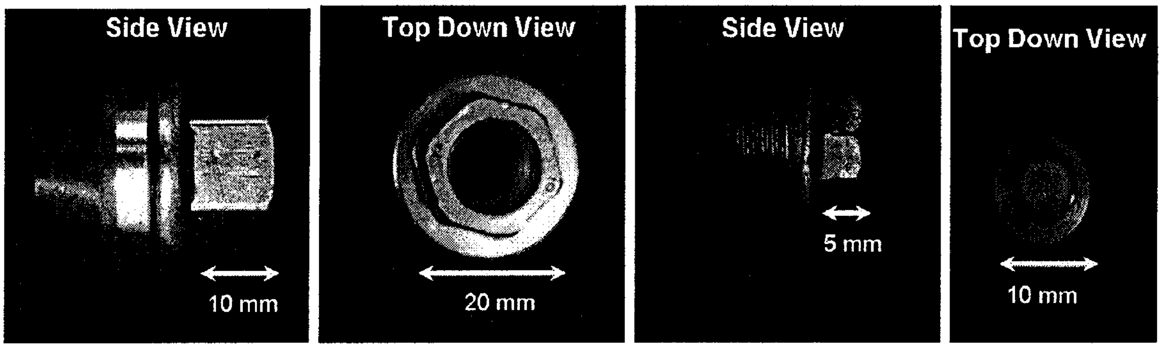

Figure 8. Picture of the bolt size showing a side view and a top down view of both the large and small fastener sizes.

degrees from horizontal (Flexion Posture, P_F), 3) wrist extended and fastener vertical, 315 degrees from horizontal (Extended Posture, P_E). Wrist flexion consisted of flexion greater than 20 degrees from an anatomical P_N. P_E consisted of minimal radial or ulnar deviation and extension of at least 25 degrees but no greater than each subject's anatomical limit (Figure 9).

(a) (b) (c)

Figure 9. Posture conditions used in the current study, a) Neutral, b) Flexion and c) Extension.

In order to eliminate biases about how the tasks should be performed, subjects did not have prior assembly line experience or experience completing FIs. In addition, subjects were screened for UE injuries that may affect results of the study. This was monitored using a pre-participation questionnaire and was posted in all advertisements related to subject recruitment (Appendix A).

Subjects were required to complete training for each condition in the study. Subjects underwent two hours of training for each of the two fastener sizes, in all three wrist postures. Conditions were randomly assigned for a total of 12 training hours. Following training, subjects were considered experienced and proceed to the testing sessions (Potvin *et al.*, 2000). Testing conditions were randomly ordered combinations of the two fasteners and three wrist postures. Testing time was a total of six hours. The summation of both training and testing equaled 18 hours of participation in the study (Table 1). In addition, subjects were given one 15 minute rest period at completion of each training or testing session if consecutive sessions were performed.

Wrist Posture	Fastener Size	Training (hrs)	Testing (hrs)
Neutral	Large	2	1
	Small	2	1
Flexed	Large	2	1
	Small	2	1
Extended	Large	2	1
	Small	2	1
Total Time		12	6
Total Participation (hrs)		**18**	

Table 1. A breakdown of participation time required by each subject for each condition performed in the study

Subjects were not permitted to participate for more than four hours of data collection on any given day. Also, subjects were not scheduled for consecutive days, thus allowing for a period of rest and to ensure subjects were actually evaluating effects of the current session and not those prior. Furthermore, holding sessions every second day allowed subjects to re-evaluate their performance from the previous session and use this as a gage for choosing future effort levels. Subjects were required to complete all 18 hours of participation within 21 days of starting the study. This ensured that subjects did not lose the effects of training.

Subjects were also asked to complete a Upper Extremity Evaluation Scale (UEES) (Snook *et al.*, 1995; Snook *et al.*, 1999) at the completion of each training and testing session. Using a modified Borg rating scale, subjects were asked to rate their discomfort/pain in various regions of the UE used to perform the tasks. These regions are defined as: *Fingers and Thumb:* the distal aspect of the phalanges to the metalcarpal-phalangeal joint; *Hand and Wrist:* from the metacarpal-phalangeal joint to the wrist joint; *Forearm:* from the wrist joint to the elbow joint. The Borg scale included three categories of ratings to be identified for each region of the UE: *Soreness; Stiffness; Numbness (Tingling)*. Each category was ranked on a 4 point scale from 0 to 3 where: 0 = No soreness; 1 = a little sore; 2 = Somewhat sore; 3 = Very sore (Appendix B).

The UEES served a number of purposes within the study. First, it allowed the investigators to track and monitor any potential injury caused from the motions associated with the task. A rating greater than 2 on the scale warranted investigation by the experimenters to ensure the posture employed by the subject accurately reflected what was intended. Thus, the UEES provided information on the intensity at which subjects worked and in the event that consistently high ratings occurred, the researcher would have intervened. Given that subjects were instructed to work at a frequency that would not induce discomfort or pain, high ratings on the UEES would indicate that subjects were either not following instructions or were no longer working in the correct postures as defined by the experimenters. The UESS was also used to encourage subjects to increase their awareness of the UE region and thus concentrate fully on the actions they were performing and the related physical sensations.

3.2 SUBJECTS

The study consisted of 24 female subjects within the age range of 18-60 years. Females were used exclusively in this study as it is common practice for many companies, in particular the one funding this study, to design for 75% of the female population. This approach is taken because on average, females have lower strength capabilities then do men and by accommodating 75% of females, you are subsequently accounting for 99% of the male population. Designing for this portion of the population is the best trade off

		Means			Standard Deviations		
Age	n	Height (m)	Weight (kg)	Age (yrs)	Height (m)	Weight (kg)	Age (yrs)
20-30	8	1.7	60.1	22.8	0.1	9.1	3.5
31-45	8	1.6	62.3	38.1	0.1	10.7	4.5
46 +	8	1.6	80.8	54.5	0.0	10.3	4.7

Table 2. Anthropometric measures by age category

between economics and ergonomics. The cost associated with accommodating more than 75% of the female population increases considerably with little added benefit to the safety of the working population. Subject's age, weight, and height can be viewed in Table 2. Eighteen of the 24 subjects completed the *Edinburgh Handedness Inventory* to determine their handedness (Appendix B). Results showed that of the 18 subjects who completed the questionnaire all were right handed. All subjects were screened for UE injuries prior to beginning data collection and also for prior experience in the automotive assembly industry as well each subject's height and weight were collected at this time. This information was collected with a questionnaire (Appendix B).

3.3 INSTRUMENTATION

To collect the required data a number of recording devices were employed.

3.3.1 Fastener Initiation Device

A device was designed to simulate the action used in the industry to initiate fasteners. This device was fixed to an adjustable jig stand, permitting variations in vertical height (30mm resolution) as well as differing mounting angles (45 degree resolution) (Figure 10). The FI simulation device consisted of a horizontally positioned rod (70 mm long with a diameter of 10 mm) with a threaded proximal tip to accept each of the fasteners. The distal aspect of the rod attached to roller bearings which ensured constant friction so that subjects experience a consistent, yet low torque resistance (0.3 Nm), throughout the

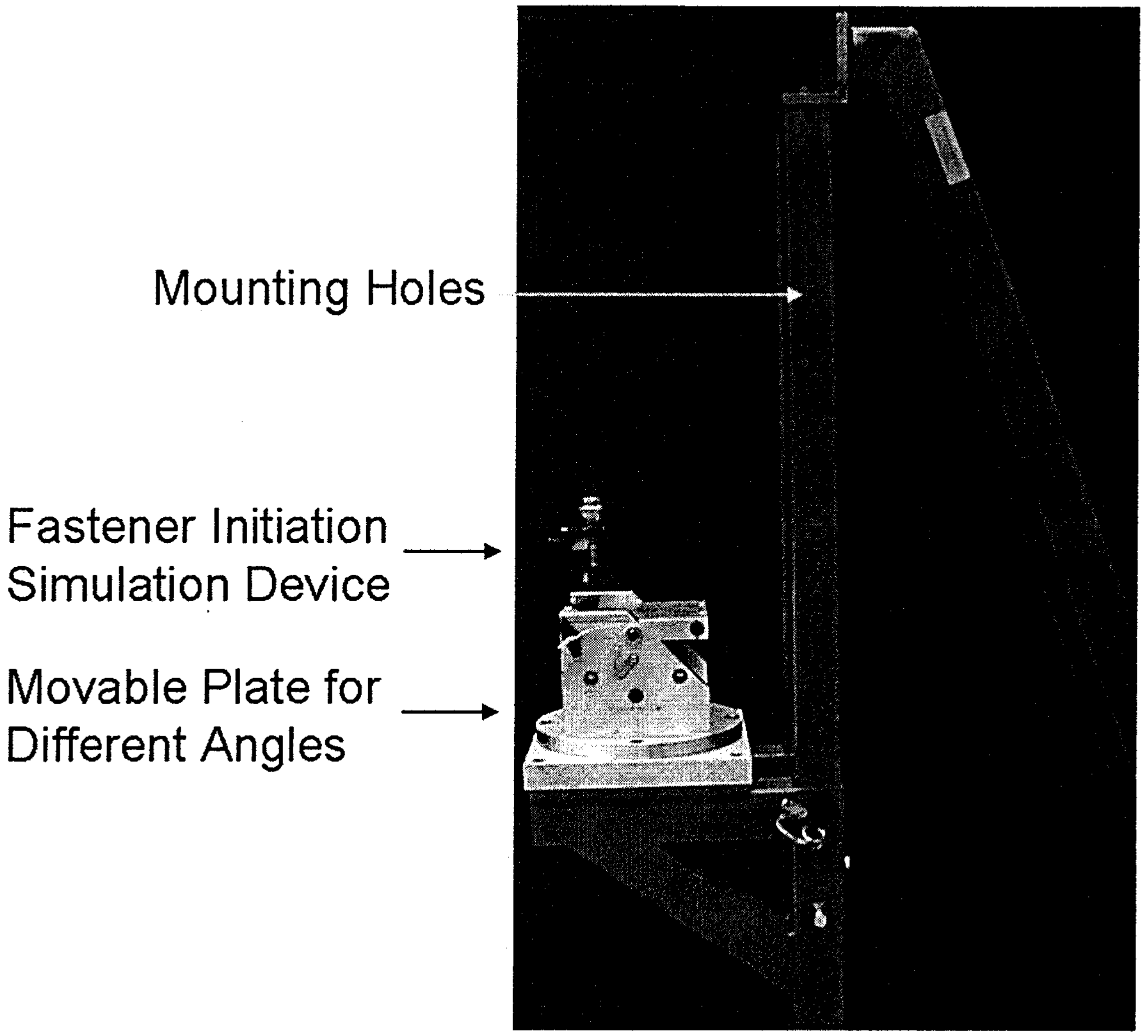

Figure 10. The adjustable jig structure which houses the fastener initiation device. Mounting holes allowed for adjustments for height.

experiment. At the distal end of the rod a "Full 360 degree Smart Position Sensor" (continuous reading potentiometer) (Vishay Spectrol, Vishay Intertechnology, Inc, Malvern, PA) was attached to measure the total angular displacement during each FI (Figure 11).

The potentiometer used in the device served two main purposes. Firstly, it tracked the angular rotation of the fastener produced by each subject. This was important as it ensured that complete FIs were achieved. Secondly, displacement data recorded by the potentiometer was mathematically differentiated to obtain velocity data of each effort during each of the FI performed.

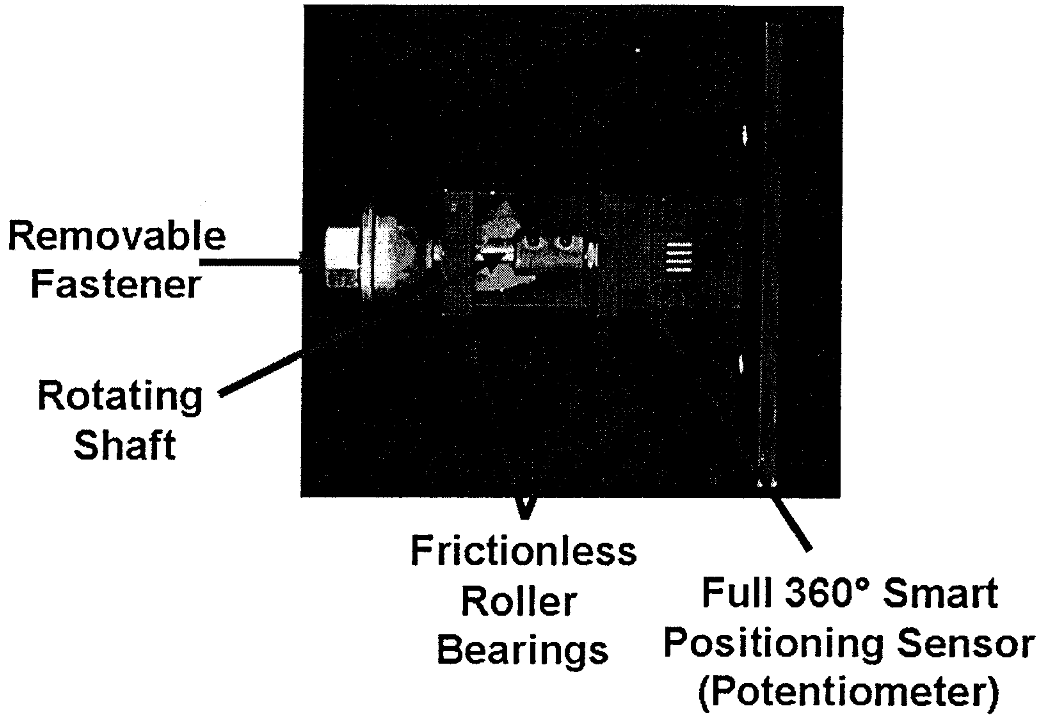

Figure 11. Diagram of the Fastener Initiation Simulation Device.

3.3.2 Electromyography

Six channels of bipolar disposable surface electromyography electrodes were used to measure individual muscle electrical activity contribution as a percentage of their maximum voluntary exertion (MVE) during each FI in each of the experimental conditions. Four channels of *disposable bipolar Ag-AgCl surface electrodes 10 mm* (Medi-trace disposable electrodes, Graphic Controls, Chicopee, MA) and two channels of *reusable electrodes 4 mm* (Coulbourn Instruments, Allentown, PA) were placed in parallel on each muscle belly in the direction of its line of action. The two channels using the reusable electrode were designated to measure the electrical activity of the FDI and the Thenar muscle and represented the index finger and thumb activity during the FI task. Two channels of EMG using disposable electrodes were designated to the forearm musculature with one channel placed on the ECU (to represent extension of the hand and wrist) and one on the FCU (to represent wrist flexion). Two additional channels of

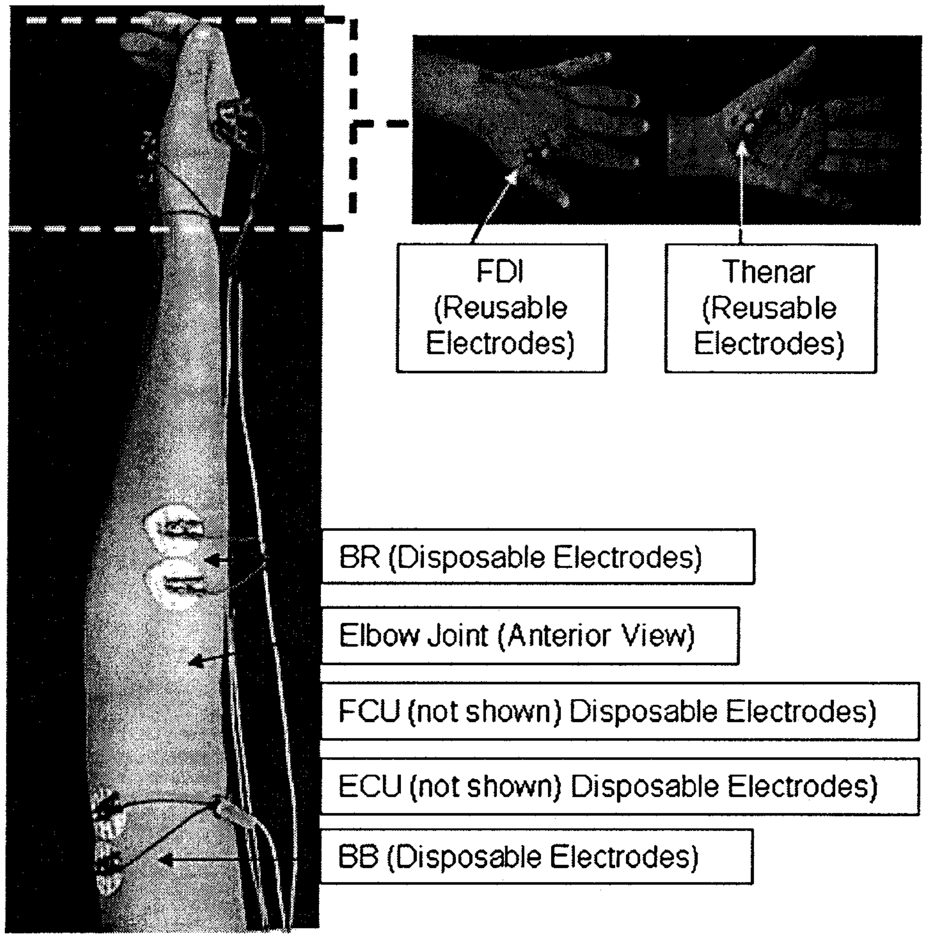

Figure 12. Electrode Placement for the BB, BR, FCU, ECU, FDI and TE

EMG using disposable electrodes were designated for the humeral area of the arm. One channel was assigned to the BB (capturing elbow flexion and forearm supination) and the second channel was placed on the BR (capturing forearm pronation). Electrode placement can be viewed in Figure 12.

3.4 EXPERIMENTAL PROTOCOL

3.4.1 Instrumentation Application

At the start of the first training session, subjects were given a verbal explanation of the purpose of the study and were introduced to the instrumentation in order to familiarize themselves with the set-up.

For the testing sessions, bipolar Ag-AgCl EMG electrodes were placed on the UE. Location of electrode placement was as follows and can be viewed in Figure 12: FDI; approximately 50% of the distance between the thumb and index finger on the posterior aspect of the hand, Thenar; located on the anterior or palm side of the hand approximately 33% of the distance from the wrist to the index finger and approximately 33% of the distance from the base of the thumb to the medial border of the hand, ECU; at approximately 50% of total length from the olecranon to the wrist on the medial/posterior border of the forearm, FCU; at approximately 30% of total length from the olecranon to the wrist on the medial/anterior boarder of the forearm, BB; approximately 50% away from the proximal (shoulder) aspect of the muscle on the anterior surface, BR; at approximately 20% of the distance from the elbow joint to the wrist joint on the anterior/medial aspect of the forearm (Saitou *et al.*, 2000). Also a common ground electrode was placed on the medial epicondyle of the humerus. These areas were cleansed with an alcohol solution to ensure adequate electrode surface contact with the skin. Prior to placement of each pair of electrodes a small mark was placed on site of electrode placement using a permanent marker to ensure consistent placement throughout the study. Subjects were asked to maintain these marks by re-applying them if they faded. Electrodes were placed on the marks and connecting wires were attached. Loose wires were adhered to the UE with mesh-style gauze to ensure they do not impede movement.

For both the training and testing sessions subjects were positioned in a chair and the jig was adjusted to their height, such that all FIs were completed with the forearm perpendicular to the humeral aspect of the UE (Figure 9). The FI simulation device was manipulated to accommodate each assigned wrist posture throughout the study as outlined in section 3.1.

3.4.2 Training Sessions

The EMG data was not collected during training however, potentiometer data was recorded for analysis. Customized software was developed to collect the study data. Following completion of each FI, an auditory cue provided by the computer software indicated the finishing point which also signified that a new FI could begin when the subject was ready. Also, as mentioned earlier subjects were not allowed to perform more than 2 training sessions (4 hours) in one day and were not permitted to participate in consecutive days.

Throughout all training sessions, subjects were asked to choose the repetition rate of FI's and velocity of each FI effort. Subjects maintained a constant posture while performing each rotation but were not required to hold that position when not performing the task.

During training and testing sessions, subjects were constantly monitored by the experimenters to ensure the desired posture was being maintained. Instructions were provided and adjustments to the devices were completed on an as-needed basis. Subjects were also periodically reminded that the intensity of work should be steady but must not induce discomfort. Subjects had the ability to adjust rate of velocity and the number of efforts used to complete each FI. Data from each rotation was collected and stored in a personal computer. The end of each session was identified by a visual cue from the computer. Subjects were provided with a 15 minute break after each training session and then were required to complete a UEES for the session just completed.

Training sessions allowed subjects to become acquainted with the devices and conditions involved in the study. The intent of training was to prepare subjects for testing, ensuring that they were able to choose the appropriate acceleration and repetition rates for each condition.

3.4.3 Testing Sessions

Following all training sessions, subjects were required to complete six one-hour testing sessions. During the testing session both potentiometer and EMG data were collected. The protocol for the application of EMG was described in Section 3.4.1. Potentiometer data were collected in the same manner as for training session which can also be reviewed in Section 3.4.2. As with the training protocol, subjects were not allowed to perform more than 4 testing sessions (4 hours) in one day and were not permitted to participate in consecutive days.

Prior to the each testing session (each time electrodes were attached), MVE's and signal noise (bias) trials were collected for all six channels. For the signal noise collection subjects were positioned so that their arm was completely supported by a table. Subjects were then instructed to completely relax the musculature of the UE. Following the signal noise collection, subjects were than placed into postures that were most mechanically advantageous and provided isolated muscle contractions for each of the six muscles. Subjects then exerted their maximal UE force during dynamic movements of the muscle against a resistance provided by the experimenter. Three trials of MVE data were collected and each trial comprised of three second exertions. All MVE data were logged for future analysis and were also used to normalize EMG from the testing sessions.

3.5 DATA ACQUISITION AND PROCESSING

All instrument data was collected and stored on personal computers, each computer was equipped with a 12-bit resolution Analog to Digital (A/D) conversion board (National Instruments, Austin, TX). All instrument data was collected and processed with custom designed software developed through the LabVIEW software package (National Instruments, Austin, TX).

3.5.1 Potentiometer

A potentiometer was used to record the angular displacement of the simulated fastener. The potentiometer signals were sampled at 1000Hz and then linearly interpolated to a final sample rate of 50 Hz and stored for analysis. A FI was considered complete only if the angular displacement exceeded a 648 degree threshold (or 90% of 720 degrees). All other angular displacement data were disregarded. The angular displacement data were mathematically derived using a two point method (below) to determine the velocity time-history during each FI. As well, velocity data were used to identify the beginning and end point of each effort. It was the sum of each effort that made-up a complete FI (Figure 13).

$$v_n = \frac{d_n - d_{n-2}}{t_n - t_{n-2}}$$

where: v_n = velocity
d = displacement (from potentiometer)
t = time

For each FI and effort, the start and end point of each recording was truncated. The start point of each FI was defined as 0° and ended when the subject reached a 720° threshold. To truncate each effort, zero velocity was the starting point and the end was reached when the effort returned to zero velocity once again. These data points were used for EMG windowing procedures to ensure only the EMG from the FI and efforts were being analyzed (Figure 13).

3.5.2 EMG Data

All EMG signals were differentially amplified (Common Mode Rejection Ratio (CMRR) >80 db) 1000 to 5000 times using an amplifier with an input impedance of $>10^{12}$ ohms, set prior to sampling. Each sEMG signal was A/D converted at 1000 Hz, rectified, and averaged across 20 ms windows to result preliminarily linear envelope EMG with a

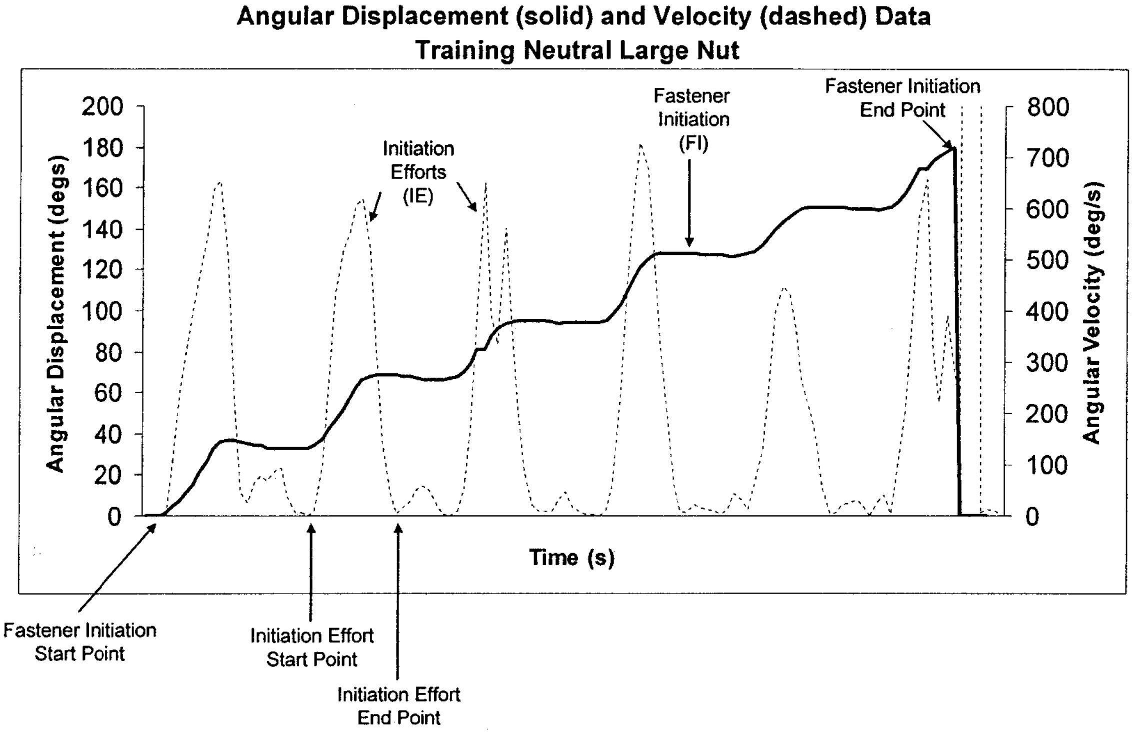

Figure 13. Sample potentiometer data for a fastener initiation and initiation effort.

rate of 50 Hz. This procedure was necessary so that the computer could process online data as well as cope with the large file size of data collected over a one-hour period.

All EMG signals collected during testing sessions were subsequently low passed filtered utilizing a 2nd order Butterworth filtered with a frequency cut-off of 1.5Hz for the MVE's and 2Hz for testing session EMG. A lower cutoff frequency was used to smooth the EMG data so that the peak of each EMG curve was used to represent the MVE as opposed to taking the average amplitude of the data points around the peak of the curve. Following the filtering process, EMG data was truncated based on the start and end of each of FI as determined from the displacement of the potentiometer (described in Section 3.5.1). This ensured that the EMG analysis was focused on data collected during the FI task, ignoring data recorded in between FIs. The EMG amplitudes from each FI obtained from this truncating technique were then averaged over the testing session. Throughout this document the data obtained from this technique is referred to as aEMG (average EMG). In addition, EMG was further truncated based on the effort start and end points determined from the mathematically differentiating the potentiometer data (angular displacement) as described in Section 3.5.1. This allowed for sEMG data to be analyzed for each discrete initiation effort (Figure 13).

3.6 DATA ANALYSIS

The dependent variables in this study include: frequency of FIs completed during each minute, duration of each FI, quantity of efforts/FI making up each FI and individual muscle electrical activity as a percentage of maximum during each FI and effort (measured with EMG).

Data from the last 20 minutes of both the training and testing sessions were averaged for each condition and used in the analysis. Repeated Measures Analyses of Variance (ANOVA) ($p<0.05$) were used to determine statistically significant main and interaction effects in the 3 posture (within) X 2 fastener sizes (within) x 3 age groups (between) study design. Statistical interactions were evaluated with a Tukey's significant post hoc analysis test. The post hoc analyses were used to find where means differed significantly within the main and interaction effects.

In addition, the within-subject Coefficient of Variation (COV: standard deviation as a percentage of the mean) was calculated for each dependent variable in the last 20 minutes of the testing EMG data. These COV values were averaged across subjects for each of the 6 combinations of posture and fastener size and provided insight into within-subject consistency of the EMG throughout the testing sessions. Also, the 75% capable value was calculated as the tolerance limit value (TLV) for FIs/minute using the mean and standard deviation such that TLV = mean - (SD x 0.675) for each condition. This procedure was based on recommendations from Snook (1978) and NIOSH (1981) and has been utilized by Potvin et al. (2000).

Chapter 4

RESULTS

The results of this study are divided into two sections, with the first focusing on kinematic data collected and the second on EMG data. The dependent variables associated with the kinematic data are; number of FIs performed in a minute, amount of time of each FI and the number of efforts performed in each FI. The EMG data variables examined are; percent MVE EMG activity in the BB, BR, FCU, ECU, FDI and TE muscles.

4.1 KINEMATIC DATA

Kinematic data was analyzed by averaging the final 20 minutes of each training session (last 20 minutes of the 2nd hour of participation (training sessions)) and the final 20 minutes of the testing session (last 20 minutes of the 3rd hour of participation (testing sessions)). This procedure was followed because the mean FI data from each of these sessions did not offer consistent across-condition variability (Figure 14). When comparing training to testing, training data suggested that subjects were still attending to their performance. However, test data suggested that a decrease in attentiveness occurred, which may have compromised the subjects ability to accurately assess the demands of the task.

4.1.1 Fastener Initiations per Minute

Table 3 presents mean FIs per minute data for each combination of independent variables. Following a repeated measures ANOVA analysis, fastener size data was shown to have a main effect where the large size fastener had a significantly higher acceptable frequency of FIs per minute when compared to the small (by 10%) (Figure 15). Data for FIs per minute also revealed a posture effect, showing that both P_N and P_F

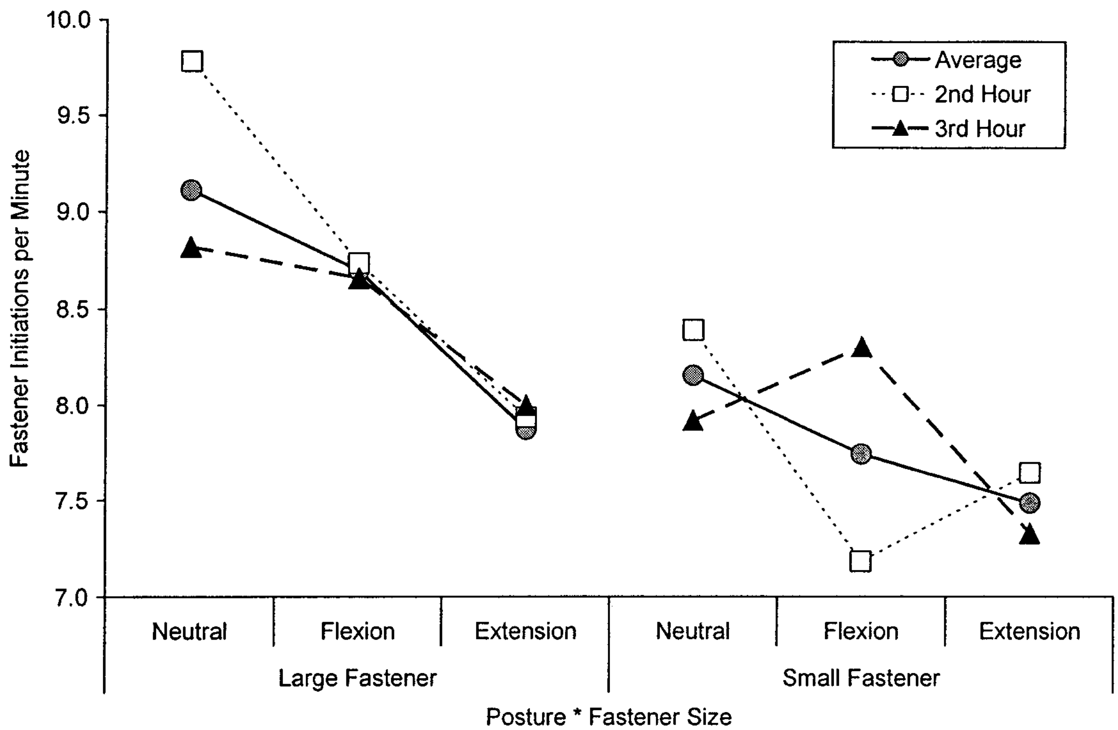

Figure 14. Fastener Initiation/minute mean data displaying the difference between the time of training, testing and averaged data. It can be seen that by averaging across the second and third hour of collection, more consistent trends are apparent (n=24).

			Posture		
			Neutral	Flexion	Extension
Fastener Size	Large	Mean	9.1	8.7	7.9
		Stdev	2.6	2.5	1.9
	Small	Mean	8.2	7.7	7.5
		Stdev	2.1	1.9	2.1

Table 3. Average Fastener Initiations per minute for each condition as calculated by the average of the second and third hour data, along with the calculated standard deviations (each condition n=24)

had significantly higher values than the P_E (by 12% and 7%, respectively) (Figure 16).

Figure 17 indicates the number of fastener initiations deemed to be acceptable to 75 percent of females studied. The P_N presented the highest number of acceptable FIs per minute, followed by P_F and P_E.

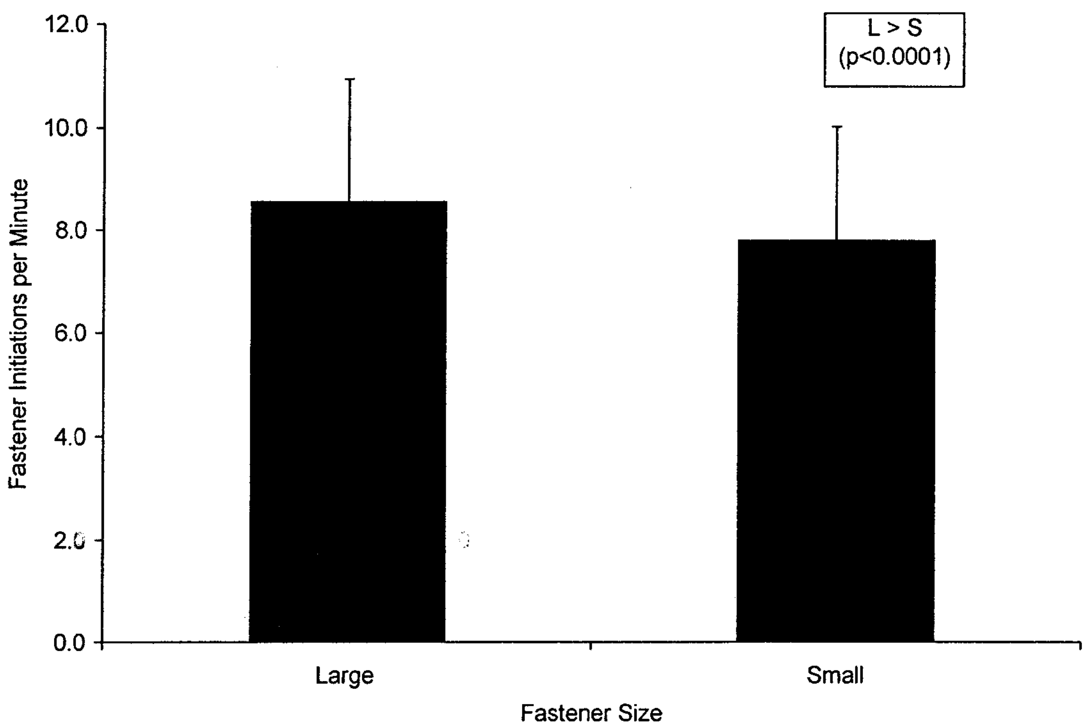

Figure 15. The main effect of fastener size on the average fastener initiations per minute. Data were pooled across all conditions according to the size of the fastener. (n=72). Standard deviations bars are presented.

4.1.2 Fastener Initiations Time

Table 4 indicates the average duration of FIs for each combination of independent variables. A repeated measures ANOVA indicated significant main effects for both fastener size ($p<0.001$) and posture effects ($p<0.0001$). Subjects took significantly more time (by 10%) to complete each FI with the smaller fastener when compared to the F_L (Figure 18). There was a significant difference between the durations for each posture. The P_F was 8% greater than P_N and P_E was 12% greater than P_F (Figure 19).

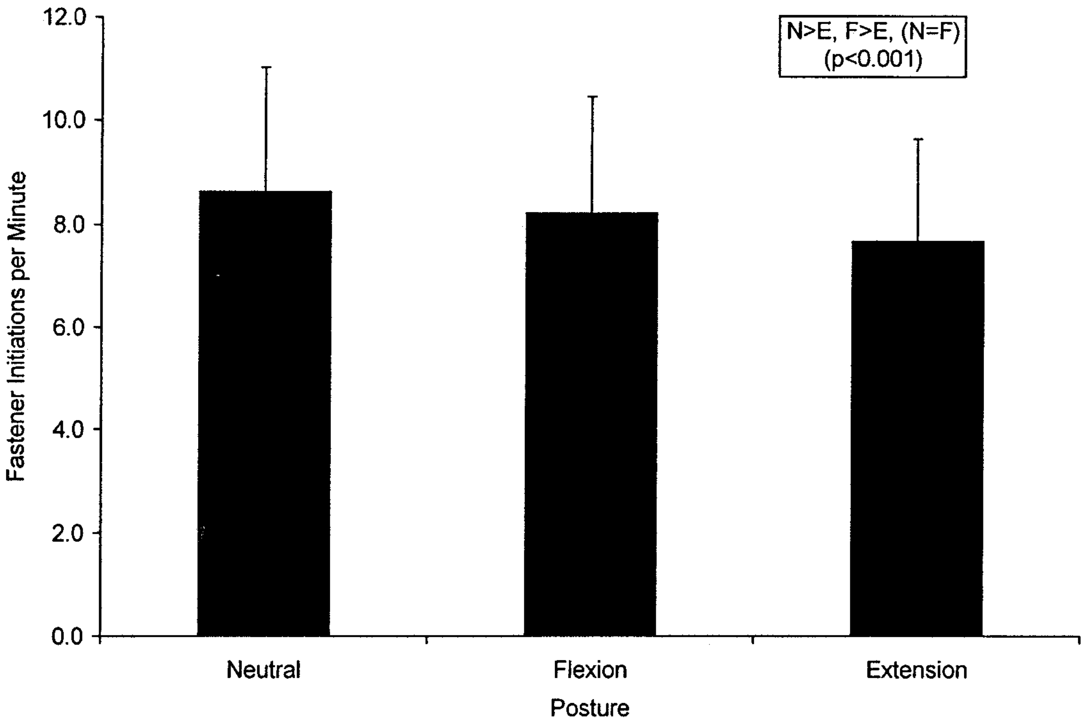

Figure 16. Main effect of Posture on average Fastener Initiations per minute (n = 48). Standard deviations bars are presented. Post hoc results are presented.

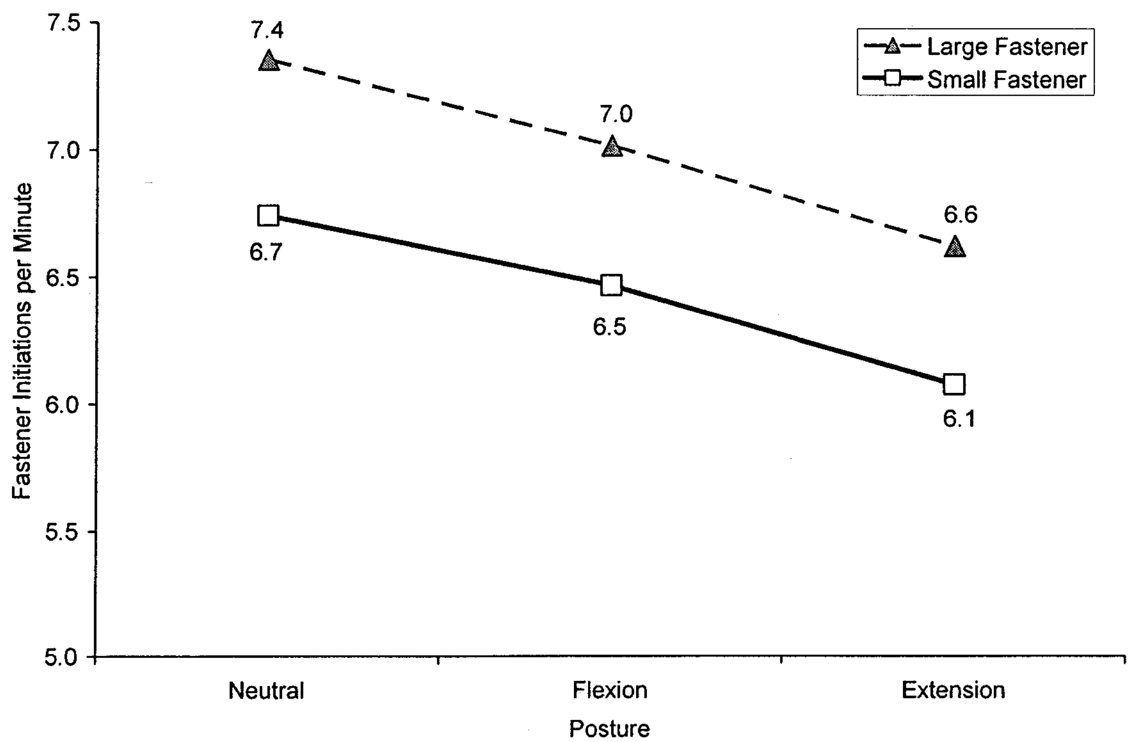

Figure 17. Proposed Tolerance Limit Values (TLVs) for Fastener initiations per minute calculated as the values acceptable to 75% of females (n = 24).

			Posture		
			Neutral	Flexion	Extension
Fastener Size	Large	Mean	2.72	2.93	3.29
		Stdev	0.70	0.73	0.80
	Small	Mean	3.13	3.27	3.47
		Stdev	0.63	0.84	0.62

Table 4. Mean duration of fastener initiations (s) for each condition. Standard deviations are also presented. (n = 24)

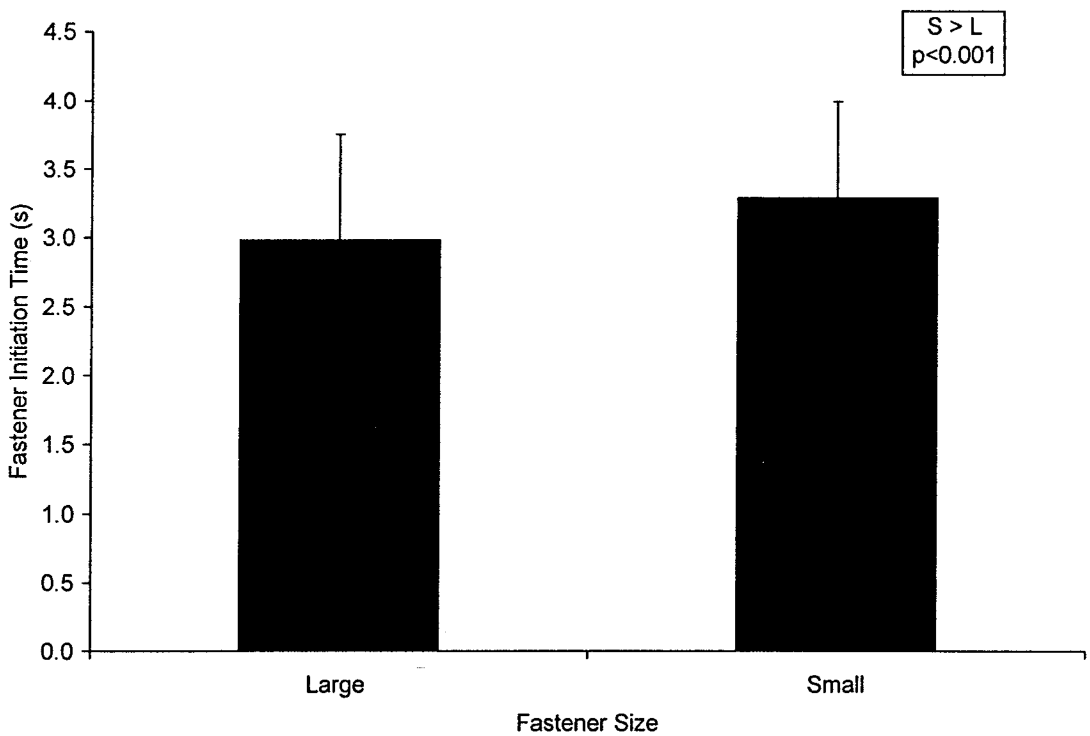

Figure 18. The main effect of fastener size on the average duration of fastener initiations. Data were pooled across all conditions according to the size of the fastener. (n=72). Standard deviations bars are presented.

4.1.3 Efforts per Fastener Initiation

A repeated measures ANOVA for number of efforts per FI indicated a significant main effect of fastener size ($p<0.05$) and posture ($p<0.001$) and a 2-way interaction between fastener size and posture ($p<0.01$) (Figure 20). For the F_L, there was a difference between means for all postures, with flexion being 18% greater than P_N and P_E being 9% greater than P_F. For the F_S means, the extension posture was 10% greater than the P_N.

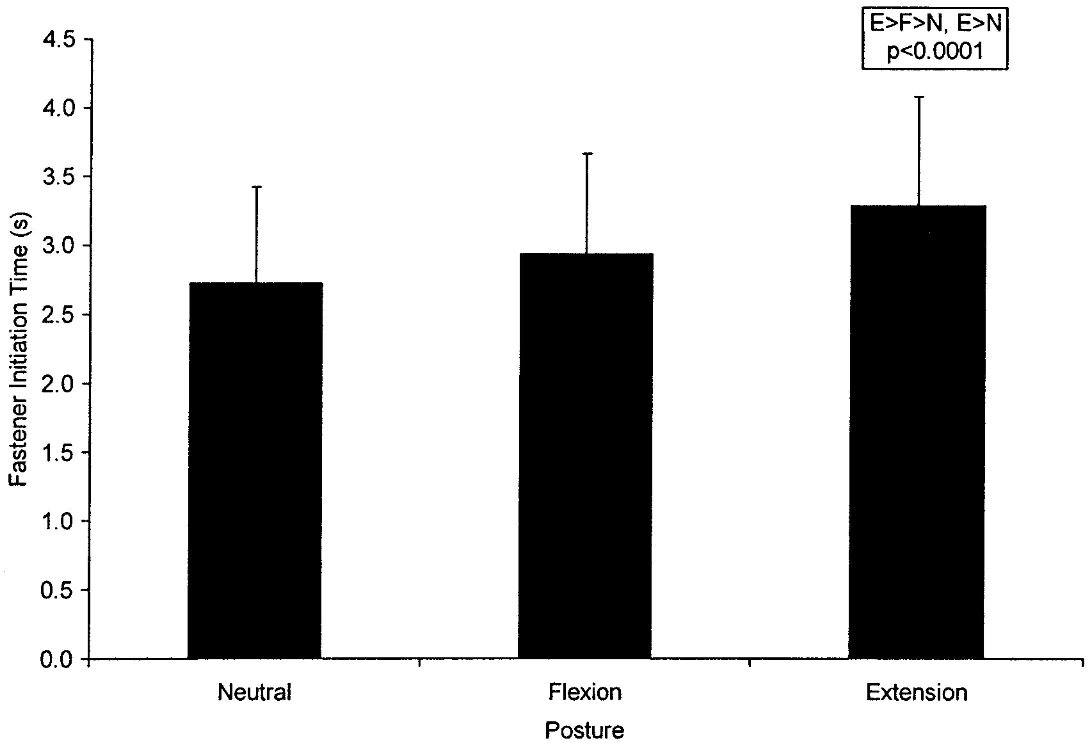

Figure 19. The main effect of posture on average duration of each fastener initiation (s) (Each posture n = 48). Standard deviations bars are presented. Post hoc results are presented.

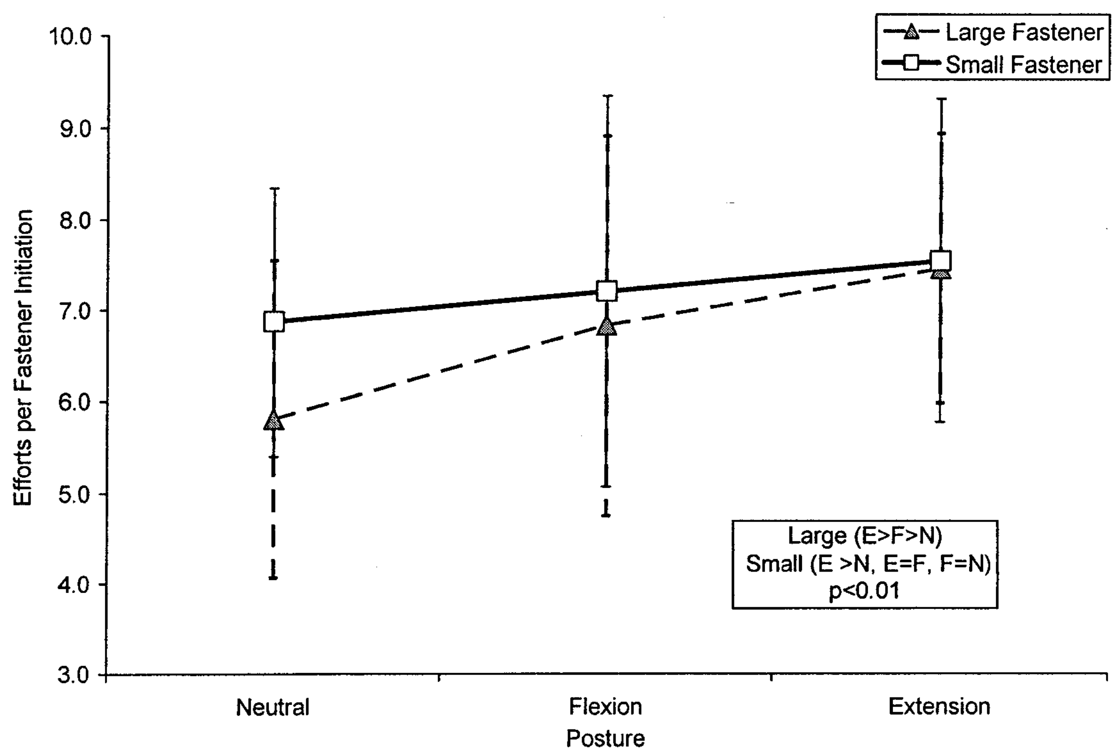

Figure 20. Interaction effect between fastener size and posture on Efforts per Fastener Initiation (n = 24). Standard deviations bars are presented. Post hoc results are presented.

4.2 EMG DATA

The aEMG amplitude was calculated over the duration of each fastener initiation. This data was used to represent muscle activation levels for each condition. This dependent measure was selected, over the pkEMG amplitude from each individual effort, as it was found to be a more reliable measure, based on lower average within-subject CVs, (23% vs 32%, Table 5). The variability in the aEMG showed that there was a range of mean COV between 18 to 29%. In comparison, the mean COV range of the pkEMG was between 29 and 41%. It must be noted that the highest variability in both the aEMG and pkEMG COV was found in the FDI muscle at 29 and 41% respectfully.

	Average EMG per Fastener Initiation						
	Large			Small			Mean
	Neutral	Flexion	Extension	Neutral	Flexion	Extension	
BB	23%	19%	21%	22%	20%	21%	21%
BR	17%	16%	21%	17%	18%	20%	18%
FCU	22%	19%	24%	25%	21%	27%	23%
ECU	16%	16%	20%	22%	17%	23%	19%
FDI	28%	34%	26%	39%	26%	25%	29%
Thenar	28%	33%	22%	31%	28%	26%	28%
Mean	22%	23%	22%	26%	21%	24%	**23%**

	Peak EMG per Effort						
	Large			Small			Mean
	Neutral	Flexion	Extension	Neutral	Flexion	Extension	
BB	38%	21%	22%	36%	24%	30%	29%
BR	24%	24%	27%	24%	25%	27%	25%
FCU	31%	28%	32%	29%	28%	35%	30%
ECU	23%	23%	26%	26%	25%	30%	25%
FDI	38%	44%	40%	51%	36%	36%	41%
Thenar	41%	44%	35%	39%	37%	36%	39%
Mean	33%	31%	30%	34%	29%	32%	**32%**

Table 5. Mean within-subject CVs (reliability) of fastener initiation EMG amplitudes. The top table represents the mean aEMG COV obtained from the entire EMG collected during each fastener initiation and an overall COV is shown as 23%. The bottom table represents the mean pkEMG COV obtained from the peak of each effort and the overall COV is shown as 32% (Each EMG & condition for both average and peak EMG: n = 19 (BB), 19 (BR), 18 (FCU), 18 (ECU), 19 (FDI), 16 (Thenar))

Muscle	Large Fastener			Small Fastener			**Mean**
	Neutral	Flexion	Extension	Neutral	Flexion	Extension	
BB	0.992	0.996	0.993	0.949	0.993	0.976	**0.983**
BR	0.979	0.975	0.984	0.974	0.976	0.982	**0.978**
FCU	0.980	0.966	0.981	0.965	0.754	0.803	**0.908**
ECU	0.981	0.779	0.916	0.766	0.820	0.990	**0.875**
FDI	0.988	0.794	0.899	0.971	0.955	0.926	**0.922**
Thenar	0.969	0.774	0.925	0.884	0.406	0.576	**0.755**

Table 6. Correlation coefficients from a comparison between pooled mean EMG data obtained from the mean fastener initiation (average) and from the mean of the efforts within a fastener initiation (peak). Note the Thenar r value as it is the only value below 0.8 (Each EMG & condition for both average and peak EMG n = 19 (BB), 19 (BR), 18 (FCU), 18 (ECU), 19 (FDI), 16 (Thenar))

In addition, average values from the two measures were generally found to be highly correlated for all muscles but the Thenar (Table 6).

Table 7 shows mean aEMG activity as a percentage of maximum in each of the posture/fastener size combinations. The highest activity was seen in the ECU for each variable combination and the highest mean activity was 14.2% MVE in both the F_L/P_F and F_S/P_F conditions. The lowest aEMG activity was reported by the BB muscle where it had a range from 1.7 to 3.0% MVE and a mean of 2.4%. Overall mean aEMG activity was calculated at 6.5% MVE.

	Average EMG per Fastener Initiation						
	Large Fastener			Small Fastener			
	Neutral	Flexion	Extension	Neutral	Flexion	Extension	Mean
BB	2.4	1.7	2.5	3.0	2.0	2.8	2.4
BR	2.8	3.4	4.4	3.8	3.3	4.2	3.7
FCU	6.0	7.3	5.8	5.9	7.2	5.4	6.3
ECU	13.3	14.2	12.6	13.2	14.2	13.7	13.5
FDI	6.3	7.5	7.5	6.2	8.1	7.4	7.2
Thenar	5.9	5.7	7.5	4.8	4.3	7.6	6.0
Mean	6.1	6.6	6.7	6.1	6.5	6.9	**6.5**

Table 7. Mean aEMG per fastener initiations as a percentage of subject's maximum voluntary contraction in each of the conditions examined in the study. The overall mean is shown as 6.5% in bold. (Each aEMG: n = 19 (BB), 19 (BR), 18 (FCU), 18 (ECU), 19 (FDI), 16 (Thenar)).

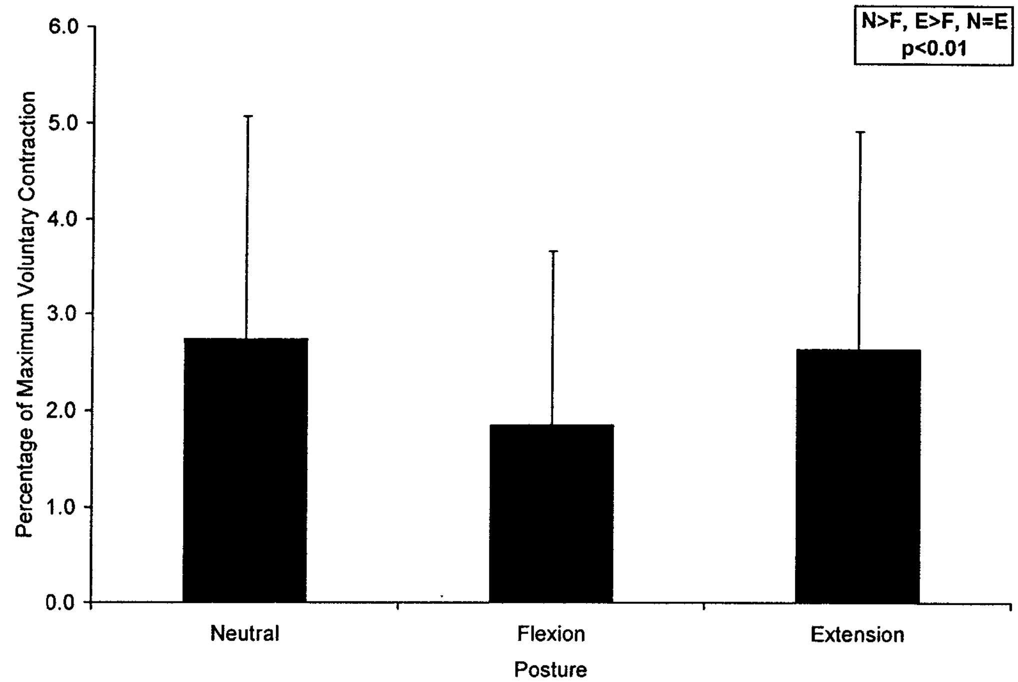

Figure 21. Main effect of posture for the biceps brachii muscle aEMG data and is shown as a percentage of maximum voluntary contraction (n = 44). Standard deviations bars are presented. Post hoc results are presented.

4.2.1 Biceps Brachii aEMG Activity During Entire Fastener Initiations

There was a significant main effect of posture for the Biceps Brachii aEMG ($p<0.01$, Figure 21). The flexion amplitudes were exceeded by the P_E and P_N by 42% and 48%, respectively.

4.2.2 Brachioradialis aEMG Activity During Entire Fastener Initiations

There was a significant main effect of posture for the Brachioradialis aEMG ($p<0.05$, Figure 22). The P_N amplitudes were exceeded by the P_E by 15% where P_F did not significant differ from P_N of P_E.

4.2.3 Flexor Carpi Ulnaris aEMG Activity During Entire Fastener Initiations

In the FCU there was a significant main effect of posture found ($p<0.05$) and a significant posture x fastener x age interaction ($p<0.05$) (Figure 23). In the 46-61 age group a) F_L/P_f resulted in greater FCU aEMG activity (by 55%) when compared to P_E; b) F_S: there was

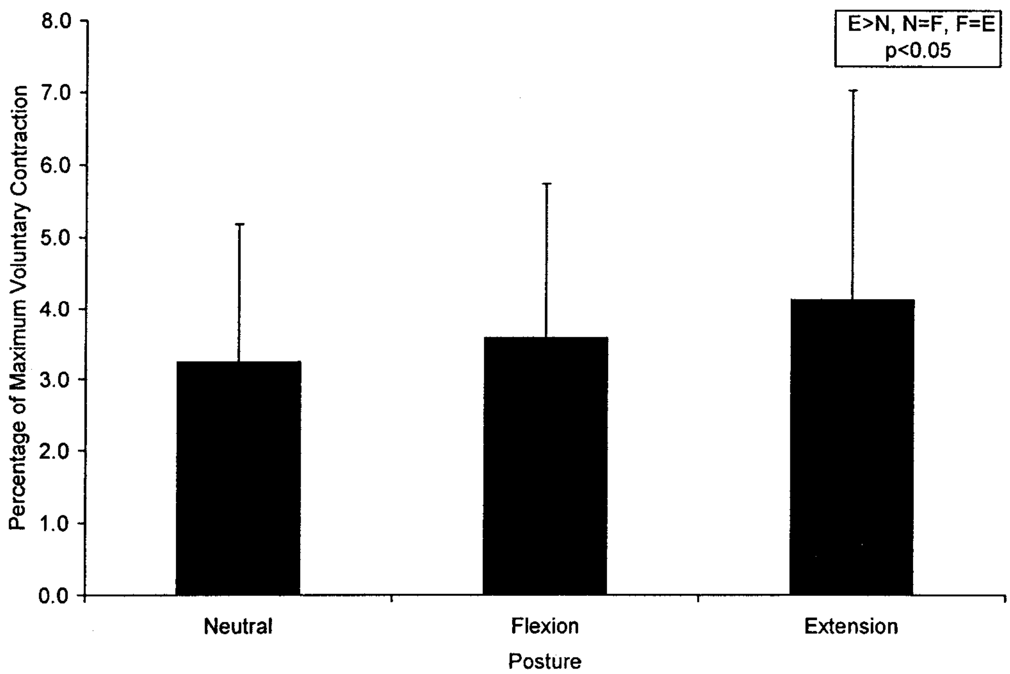

Figure 22. Main effect of posture on the brachioradialis aEMG data and is shown as a percentage of maximum voluntary contraction (n = 44). Standard deviations bars are presented. Post hoc results are presented.

significantly greater FCU aEMG activity for the P_F, compared to P_N and P_E (by 57% and 72%, respectively). In the 31-45 age category, one statistically significant difference was noted. For the F_L/P_E condition showed 14% greater FCU aEMG activity levels than the P_N condition. No significant differences in the post hoc analysis of the 20-30 age group.

4.2.4 Extensor Carpi Ulnaris aEMG Activity During Entire Fastener Initiations

As mentioned previously, the ECU muscle displayed the largest aEMG activity of all muscles for each combination of independent variables. There was a significant main effect of posture ($p<0.05$) and significant posture x fastener size x age interaction. This interaction has been grouped by age and can be seen in Figure 24. Although no significant differences were found in the post hocs of the 46-61 or 31-45 age data, a significant difference existed for the 20-30 age group, for the F_S, the ECU aEMG amplitudes were 55% greater for P_F than P_E.

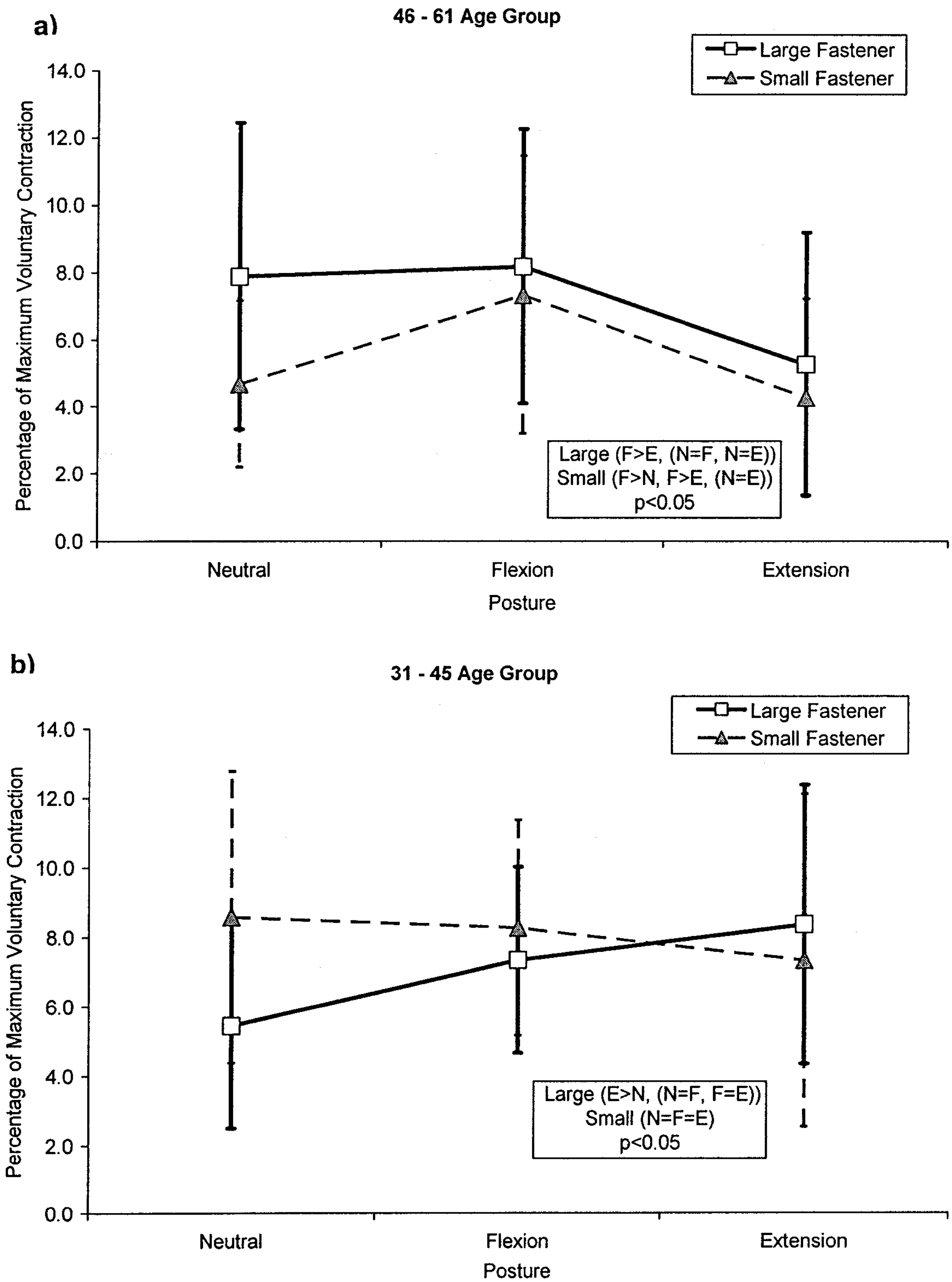

Figure 23. Graphs showing the 3 way interaction of the FCU muscle aEMG data during the fastener initiation task. The two older age groups showed significant differences while the youngest (20-30 yrs) did not (For 46 – 61 age group (a) in each condition n = 7, and 31-45 age group (b) in each condition n = 7). Standard deviations bars are presented. Post hoc results are presented.

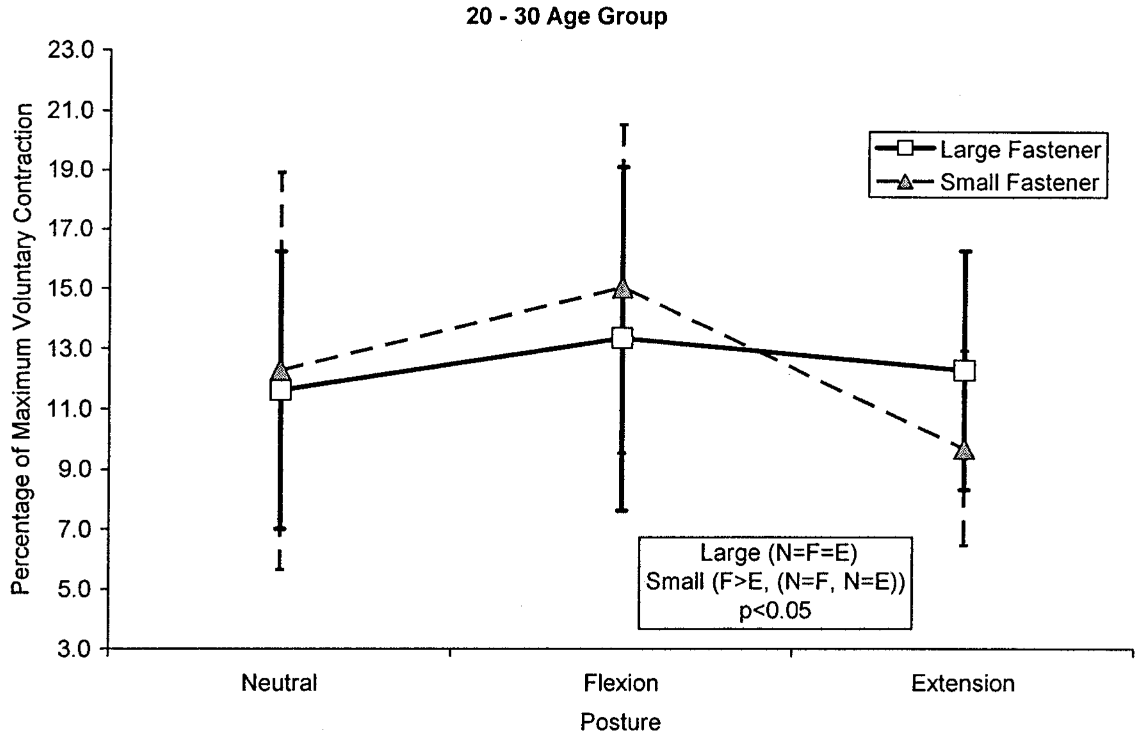

Figure 24. A graph showing the 3 way interaction of the ECU muscle aEMG data during the fastener initiation task. The two older age groups did not show any significant differences while the youngest (20-30 yrs) did (For 20 – 30 age group in each condition, n = 7). Standard deviations bars are presented. Post hoc results are presented.

4.2.5 First Dorsal Interosseous aEMG Activity During Entire Fastener Initiation

For the FDI aEMG, there was a significant age x posture interaction ($p<0.05$). The analysis did not result in any significant differences for the 46-61 or 31-45 age categories, however for 20-30 year olds, FDI aEMG activity in P_F and P_E were greater than P_N (by 87% and 92% respectively) (Figure 25).

4.2.6 Thenar aEMG Activity During Entire Fastener Initiations

There was a significant main effect of posture for the Thenar aEMG ($p<0.05$, Figure 26). The P_F amplitudes were exceeded by the extension by 48% where P_N did not significant differ from flexion of extension.

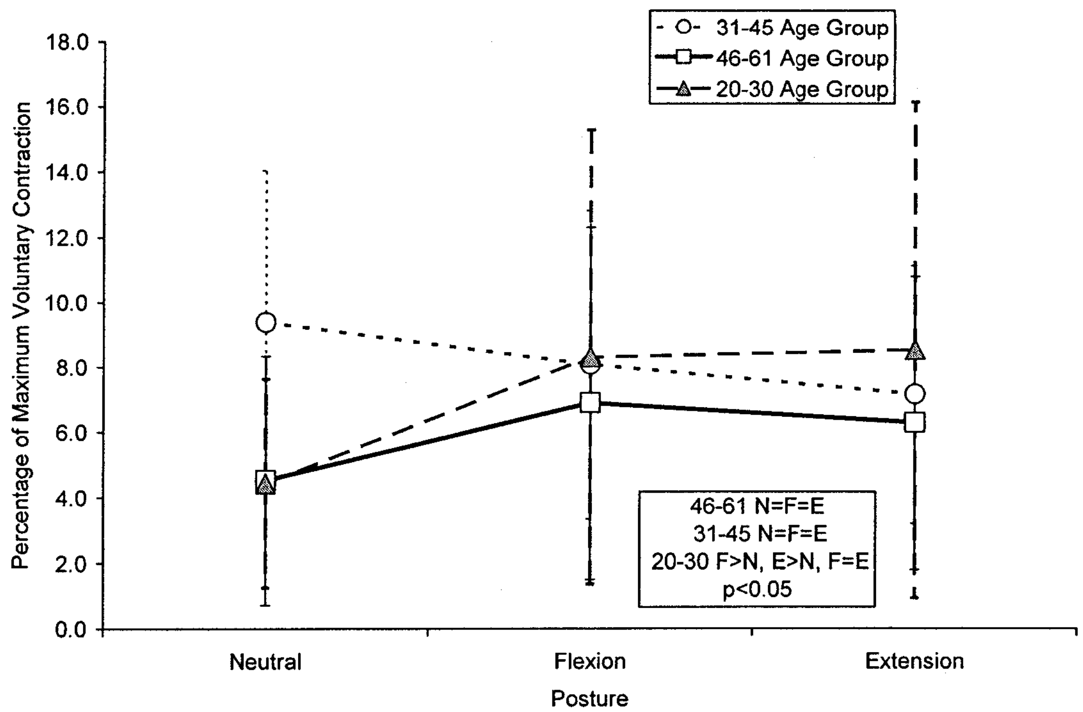

Figure 25. A 2-way interaction graph between age and posture of the FDI aEMG data which showed the only significant difference was found in the youngest age group (46-61 age group n = 12, 31-45 age group n = 16 and 20 – 30 age group, n = 16). Standard deviations bars are presented. Post hoc results are presented

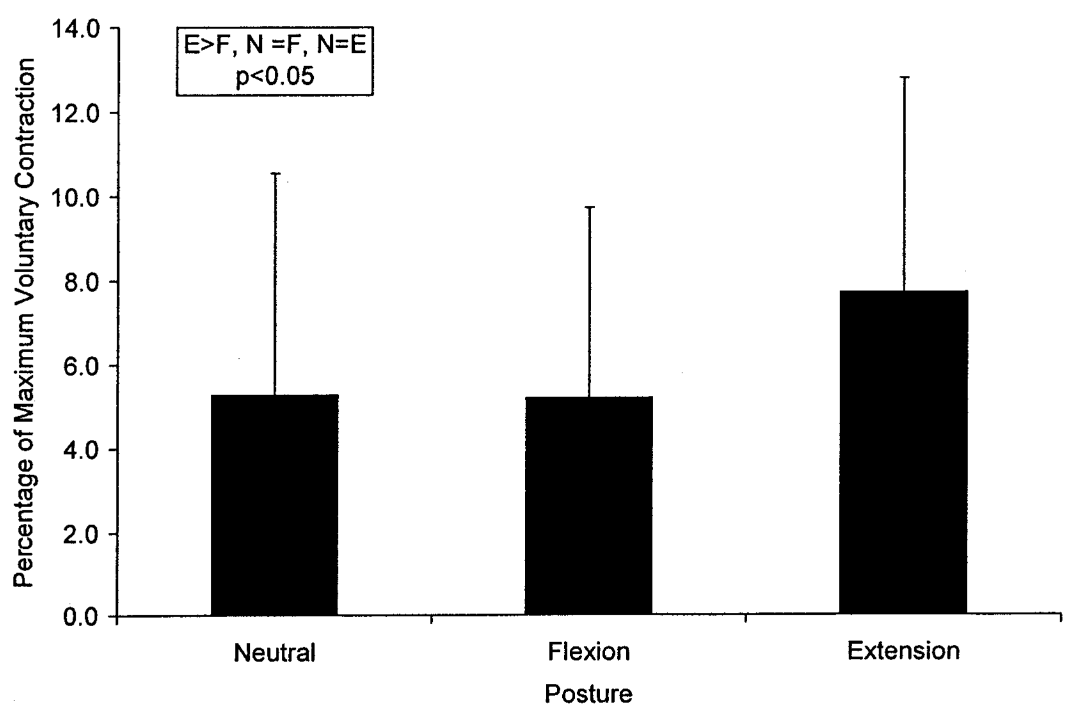

Figure 26 Main effect of posture on Thenar aEMG during the entire fastener initiations. A posture effect resulted from this data (n = 38). Standard deviations bars are presented. Post hoc results are presented.

Chapter 5

DISCUSSION

The current study was designed to establish acceptable frequencies for fastener initiation tasks in the automotive manufacturing industry. This was accomplished through the use of psychophysical and biomechanical methodologies. Twenty four female subjects performed a total of 18 hours of the FI tasks in combinations of 2 independent variables; three wrist postures (neutral, flexion and extension) and two fastener sizes (large and small). The variables measured in this study were grouped into 2 separate categories: *Kinematic*, encompassing FIs per minute (FI/min), duration (s) of each FI and the quantity of Efforts per FI (Efforts/FI); *EMG*, involving surface EMG recordings as a percentage of maximum voluntary contractions for the BB, BR, FCU, ECU, FDI and Thenar muscles during the FI tasks. To date, no literature exists on the quantification of either kinetic or muscle effort measures for FI tasks.

Kinematic data displayed an decrease in FI/min as wrist posture changed from neutral to flexion to extension. Results from the current study also showed that subjects were able to complete the greatest number of FI/min with the F_L in the P_N and the least number while using the small fastener in the P_E. This finding was similar to Klein et al (1997), where the acceptable frequency of wrist movements were examined and a neutral wrist posture resulted in the highest acceptable frequencies with a decrease occurring when subjects switched to flexion. Although Klein et al (1997) were primarily interested in force, rather than frequency, and extension of the wrist was not an independent variable, they were able to conclude that tasks involving non-neutral wrist postures are perceived as more stressful and thus cannot be performed with the same intensity.

In the current study fastener size was identified as having a main effect on the frequency of FIs, as it took significantly longer for subjects to complete a FI when using the small fastener compared to the large. Furthermore, as postures changed from either neutral or flexion to extension, an increase in the duration of FI occurred. The P_N and P_E, resulted in the lowest and highest duration of FI, respectively. This demonstrated a decrease in mechanical advantage when the wrist deviates away from neutral. A possible explanation is the change in the orientation of wrist structures with wrist deviation. When the wrist is neutral, the alignment of tissues (bones, ligaments, tendons, muscular, vascular and nerve) allows for safe movement and coordination of these structures which ensures that low force actions of the wrist can be performed with little difficulty. However, when the wrist is deviated, these structures change orientation which can produce greater demands on the tissues thus making it more difficult to perform the same task. The increase in time it took subjects to perform FIs in flexion and extension was likely due to this mechanical disadvantage which occurs with changes in orientation of the wrist structures. A study completed by Abu-Ali et al (1996) found that, with increases in the duration of hand intensive tasks, more time was needed for recovery between trials. The current subjects likely required more time to both complete the task and for rest, as tissues may have been irritated due to contact with the other tissues.

The efforts per FI data followed the opposite trend of what was seen with the frequency of FI/min. As wrist posture deviated from neutral to flexion and extension, the number of efforts/FI increased. Since fewer degrees of angular rotation could be accomplished per effort, subjects were required to increase the number of efforts to complete a full FI (720 degrees of rotation). For example, on average the greatest number of efforts/FI was 7.6 for the F_S/P_E condition, which translates to an average of 95.4 degrees of displacement per effort. This represents the smallest displacement across all conditions. It can be concluded that this size/posture combination had the greatest mechanical disadvantage among wrist structures, requiring subjects to rely more on the fingers to rotate the fastener. Because the range of motion at the fingers is less than at the wrist, the resultant fastener displacement was smaller. On the other hand, for the F_L/P_N condition, each FI was completed with an average of 5.8 efforts. This condition corresponds to the largest average angular displacement/effort at 124 degrees. The interaction between fastener size and posture, as identified in the results section, shows that both variables depend on each other in order to impact the overall results.

The muscle effort (EMG) data contributed very interesting results in which wrist posture had a significant effect for all muscles recorded. These results will be explained in detail for each muscle below.

Posture had a main effect on BB aEMG. More specifically, results showed that both P_N and P_E had higher aEMG activity than with flexion. Along with its role in elbow flexion, which was fixed at a 90 degree for this study, the BB muscle also contributes to supination of the forearm. For the task studied, both the P_N and P_E involved supination of the forearm to complete the task. However, when subjects performed the FI task in flexion, the forearm was always pronated. The significantly lower aEMG results for flexion suggests that supination could not and/or did not occur while in this posture.

BR aEMG data also showed a main effect of posture, where extension had significantly higher aEMG activity than neutral. The BR inserts on the anterior-lateral aspect of the forearm and thus as the wrist deviates into extension, this muscle is passively stretched. At this point the muscle is no longer at optimal length for contraction and therefore must be active at higher levels to accomplish forearm pronation/supination. Alternatively, in the neutral position, the muscle is at resting length and therefore can generate more force with less effort.

The FCU had a 3-way interaction between fastener size, posture and age. Of particular interest is the finding that the FCU muscle did not show any significant posture x fastener size interactions in the 21-30 age category yet, there was a significant interaction in the two older age groups. The higher FCU aEMG seen in the F_S/P_F condition can be attributed to the role of this muscle in flexion of the hand and wrist. FCU muscle activity may be highest in this condition because of the efforts required to maintain the wrist posture while simultaneously flexing the fingers. This suggests that the FCU may have served as a co-activating muscle to counteract the activity of the extensors, ultimately aiding in joint stability. Nevertheless, this observation was only seen among one age category and thus, the hypothesis cannot be generalized to other age groups without further investigation.

The ECU muscle also displayed a 3-way interaction between age, posture and fastener size. An interesting finding was that the only significant difference found within this interaction effect occurred among 20-30 year olds. This difference was found between the flexion and extension postures while using the small fastener. A possible reason that this interaction occurred is due to the flexion posture not utilizing supination as described previously, therefore the hand was solely responsible for the action providing movement of the fastener. One of the roles of the ECU, other than providing extension of the wrist, is ulnar deviation. The motion of ulnar deviation may be the main contributing action required to complete the FI task when supination cannot be performed. In addition, the grip width of the fingers of the hand was required to increase with the larger fastener in order to accommodate the larger aperture. This increase in grip width of the fingers is achieved through activation of the forearm and finger extensors. Thus, the combination of the posture and fastener size resulted in higher aEMG in the ECU. However, it must be noted that this finding only occurred in the youngest age group and in this specific condition and investigators could not explain the reason for this result without further investigation.

ECU aEMG displayed the highest activation of all muscles recorded across conditions. In fact, the largest mean ECU aEMG activity (F_L/P_F condition) was 1.8 times higher than the largest activity of the five other muscles recorded (FDI aEMG in the F_s/P_F condition). Also, the lowest ECU aEMG activity was seven times greater than the lowest activity of the five other muscles (BB aEMG in the F_L/P_F condition). This is similar to the findings of Mogk and Keir (2003), in which forearm extensor muscle (extensor carpi radialis, extensor digitorum communis and extensor carpi ulnaris) activity was greater than flexor activity (flexor carpi radialis, flexor digitorum communis and flexor carpi ulnaris) for tasks using less than 50% of maximum hand grip strength. Since subjects in the current study did not use more than 50% of hand grip strength at any time, results from these two studies can be compared. Since subjects in the current study did not use more than 50% of hand grip strength at any time, results from these two studies can be compared. Both studies suggest that the higher extensor activity, compared to flexor, can be attributed to the extensors acting as a wrist joint stabilizer to counteract both internal and external forces. The flexor muscles have greater moment arms and cross-sectional area and thus can create larger moments with less activation. This must be counteracted by higher extensor muscle activation (Gonzalez et al, 1997). It is this increased activation of the ECU that offers stability at the wrist joint against activity of such muscles as the FCU as well as moments at the wrist produced from gravity.

FDI EMG data showed an interaction between age and posture. Further analysis showed that the youngest age group (20-30 yrs) had significantly different FDI EMG activity, with the lowest values occurring in P_N, as compared to P_F and P_E. The two older age groups (31-45 and 46-61 yrs) did not display any significant differences in the FDI interaction effect. A possible explanation for why FDI activity was greater in flexion may be that the FDI flexes the fingers at the metacarpophangeal joint and this action was required to move the fastener during the P_F condition, given that wrist rotation was restricted. In addition, this muscle also contributes to finger extension at the interphalangeal joint, which was necessary in the P_E condition.

A posture main effect was found within the Thenar aEMG data, where activity was significantly higher during extension than flexion. This may be related to the technique used rotate the fastener in each posture. During extension subjects seemed to increase thumb opposition when holding the fastener, more so than in flexion. Thumb opposition is largely performed using the Thenar muscle.

5.1 HYPOTHESES REVISITED

1. Training sessions will result in consistent and low Coefficient of Variation values pertaining to within-subject variability on the maximum acceptable frequency of FIs.

This statement was made prior to adjustments in the methodology and since then it was decided that subjects would not be notified at the completion of each minute during data collection. This change was implemented to limit confusion for the subjects. An additional variable may have taken the subjects attention away from the FI tasks, potentially altering their assessment of an acceptable frequency. In the end, the total number of FIs was measured over the collection period and divided by time so that there were no recorded number of FIs for each minute. As a result, calculating the coefficient of variation (between each minute performed) was not possible. Thus, this hypothesis statement was neither proven nor disproved and has been removed from the study.

2. *Psychophysical data will show a statistically significant interaction (p<0.05) between wrist posture and fastener size. Further post hoc analysis will show that the highest acceptable frequencies will be exhibited when manipulating the large sized fastener in a neutral wrist posture. This will be greater than when in the flexed and extended wrist postures using either fastener size.*

The current results failed to reject the null hypothesis, as there was no statistically significant interaction between wrist posture and fastener size for FI/min. However, both the fastener size and posture had significant main effects on FI/min without any interaction. The second part of this hypothesis proved to be true as higher frequencies were observed with the larger fastener size. Also, the posture effect showed a significant difference ($p<0.05$) as neutral and flexion had greater FIs per minute than did extension. Also, the highest acceptable frequencies were observed with the F_L/P_N condition.

3. *Surface EMG data will show that wrist posture will affect the EMG amplitude of recorded muscles. Specifically, variance in muscle force contributions will occur with changes in postural conditions. When in a P_N, the Extensor Carpi Ulnaris will show the highest surface EMG amplitude. For wrist flexion, highest surface EMG amplitudes will be noted for the Brachioradialis and when in extension the Extensor Carpi Ulnaris will show the highest surface EMG amplitude.*

Surface EMG data allowed for investigators to reject the null hypothesis. Posture had a main effect on three of the recorded muscles (BB, BR and TE) and an interaction effect on the other three (FCU, ECU and FDI). However, muscle activation levels did not entirely reflect this hypothesis as ECU aEMG showed the highest level of activation in all three postures, including flexion. The contribution of ECU aEMG was initially underestimated during flexion as the ECU appears to plays an important role in wrist joint stability. This consideration was overlooked when the hypothesis was originally posed.

4. Reports of discomfort will be greater for flexion than for the P_N. Also, discomfort will be noted in the distal aspect of the digits for all conditions due to the constant finger-fastener interaction

Reports of perceived discomfort have since been removed from the study. Instead of including this measure in the data analysis, the rating scales served an alternate purpose. The researchers felt that this type of tool was a good way to enhance the subject's awareness of their work intensity and it also served as a checkpoint for the investigator to ensure subjects were not experiencing high levels of discomfort while performing the task.

5.2 RELIABILITY

As previously mentioned, subject reliability was measured by calculating the average within-subject coefficients of variation for the EMG activity of each muscle. Within-subject COV's were, on average, 23% when collapsed across means for all posture and fastener size combinations. COV values ranged from as low of 16% to as high as 39%. The average COV of 23% is higher than reliability values obtained for recent psychophysical studies by Potvin et al (2004) and Andrews et al (2004) of 10% and 9%, respectively. However, it must be noted that the tasks investigated by both Potvin and Andrews were designed to measure the force of insertion for automotive electrical connectors and hoses, to a set frequency. Furthermore, EMG was not used as a dependent measure in either study and EMG typically has higher COVs than force measures. In addition, while the EMG COVs were relatively large, so to were the EMG amplitudes such that the absolute magnitude of within-subject variability for each condition had a maximum of only 3.2% MVE (ECU, small fastener, extension) and an overall average of 1.5% MVE. Thus, it appears that muscle activation levels were kept within a relatively small range for each muscle, fastener and posture.

5.3 LIMITATIONS AND ASSUMPTIONS

In the current study the limitation and assumptions associated with psychophysics deserve some attention. Psychophysics is based on subjective measurements made by the participant rather than an objective appraisal. However, this methodology has been well accepted in science and the results from psychophysical studies have been used on several occasions for the development of work guidelines of TLVs in the manufacturing industry. Psychophysics permits realistic simulation of tasks performed in industry without interference from obtrusive instrumentation and thus it has become a widely used research tool (Snook 1985).

The use of unskilled subjects may have had an effect on the results as they were not accustomed to the industrial environment or procedures. Potvin et al (2000) showed previously, when studying dynamic hand impacts for interior trim panels within the automotive industry, that the performance of unskilled subjects did not differ from that of experienced assembly line operators. For the current study, 12 hours of training and 6 hours of testing on the simulation device were provided prior to testing (3 hours of expose to each posture and fastener size combination). This was done to ensure subjects were very familiar with the task and could offer a valid assessment of the activity. This protocol proved to work well given the acceptable reliability of the EMG data, where the collapsed mean across all muscle within-subject COVs was 23%. A laboratory setting was chosen for this study over a true industrial environment to allow for complete control over posture and to ensure subjects were able to fully concentrate on their performance.

Due to the vast number of wrist postures and fastener sizes conditions possible in industry, this study was designed to span the range of scenarios commonly seen in industry. Fastener sizes were chosen based on the largest and smallest sizes used in the automotive industry. This approach will allow for mathematical interpolation of results to predict acceptable limits for a variety of fastener sizes.

There are a number of factors to consider when applying the recommended TLV's in industrial settings. Cotton gloves were worn by subjects throughout the study as this task is completed in the industry while wearing gloves, which may not always be the case at work. The application of gloves can be an issue for force-related tasks as the interaction between glove and object can alter tactile sensitivity and thus, forces exerted. However given that the current FI task was primarily frequency based, the use or non-use of gloves is not expected to alter the TLVs obtained in this study. As well, the extreme of each posture was not examined whereas in industry this cannot always be controlled for. However, given the increased participation of ergonomists in the design of workstations, it is anticipated that extreme postures would be identified and changed prior to a worker ever performing the actual job. Also, different fastener shapes and sizes, as well as differing resistance, from such things as 'metal burs' and the use of lubricants, should be considered when applying the recommended TLV's.

Originally, the researcher intended to assess the final 20 minutes of data collected during testing. However, this approach was modified following an examination of the results once all of the data was collected. It was found that during the last 20 minutes of testing, subjects showed relatively little variability across posture conditions (neutral, flexion, and extension), however, the opposite was shown during the last 20 minutes of the second hour of training. Training data revealed that subjects performed fewer and fewer FI/minute, as postures changed from neutral to flexion and finally extension. Based on this information, an average was taken from the last 20 minutes of the second and third hours of testing as the most accurate representation of the task. The investigators feel this was a result of a study limitation that did not allow for subjects to validate their work intensity during the sessions. Previous psychophysical studies by

Potvin et al (2004) used a method of altering subject chosen acceptable force output in an electrical connection task in 15 minute intervals. This protocol was used to prevent subjects from becoming comfortable with their current setting as well as validate that subjects were choosing a level of resistance that was acceptable to their tolerance limit. However, in the current study, it was not possible to alter frequency on the subjects. It must be noted, however, that EMG data were recorded only during the last 20 minutes of the third hour, so it was not possible to do a similar combination of the second and third hours.

Since subjects were tested for only one hour, and a full work day is usually considered to be 8 hours, it may have been difficult to accurately predict what their acceptable frequencies would be for an entire work day. Nevertheless, this approach was chosen based on collection time constraints, given the number of subjects studied. Further, collection periods lasting 8 hours would limit the number of variables that could be studied. A total of 3 hours (2 hours training and 1 hour of testing) were performed in each of the six conditions, to give the subjects an opportunity to psychophysically evaluate their perceptions on the task. It is believed that the total amount of time spent training and testing for each condition was sufficient to ensure valid estimate of acceptable frequencies. This is supported by previous work employing psychophysics to evaluate a drilling activity (Marley & Fernandez, 1995). No significant differences were found for data collected over 30 minutes, 4 hours and 8 hours. Also, in a manual material handling investigation (lifting, lowering, pushing, pulling and carrying) that used a psychophysical approach, it was found that weights selected for tasks lasting 40 minutes did not differ significantly from those performed over 4 hours (Ciriello, et al 1990).

5.4 RECOMMENDED ACCEPTABLE LIMITS

Snook (1978) used psychophysics to establish guidelines for recommended acceptable limits for lifting, lowering, pushing, pulling and carrying tasks. A three times greater risk of low back injury was found when jobs were designed to be acceptable to less than 75% of the population. The TLV's from this current study were mathematically calculated using the method proposed by Snook (1978) using the mean and standard values to determine what is acceptable to 75% of the female working population (mean - (0.675 x standard deviation)) for the frequency of fastener initiations. These recommended TLV's can be viewed in Figure 4. The range of the TLV's in the F_L condition were found to be 7.4 to 6.6 FI/min during the neutral and extension posture respectively. In the F_S condition, values ranged from 6.7 to 6.1 FI/min for the neutral and extension posture respectively.

5.5 WRIST POSTURE AND FASTENER SIZE EFFECTS

The current study offers a number of interesting findings. The kinematic data presented in this paper offer an interesting discovery related to psychophysics. As the number of exposure hours increased for this frequency-based task, subjects had more difficulty deciphering the effects of different conditions. This was seen in the FIs per minute (FI/minute) data where the frequency of FIs was affected more by both posture and fastener size for the second hour of participation (training sessions) than in the third hour. For this reason, the researchers chose to evaluate an average of the last 20 minutes of second and third hours. However, further investigation is required to determine the appropriate balance for training in psychophysical based studies. In particular, frequency based tasks have been largely under investigated and thus require future attention (Ayoub and Dempsey, 1999).

Another interesting finding identified within the kinematic data was that, as the frequency of FIs per minute increased, the quantity of efforts per FI decreased. This occurred for both fastener sizes as postures changed from neutral to flexion and than extension. In fact, the greatest number of FIs/min and lowest efforts/FI occurred during the P_N. In contrast, the P_E displayed the lowest number of FIs/min and greatest efforts/FI. However further analysis of kinematic data revealed that subjects were consistently willing to perform approximately one effort per minute, regardless of condition. When pooled across all conditions, subjects were willing to perform an average of 56.6 efforts/min with a COV of only 4% across conditions. Although subjects performed about one effort/min, the degrees of rotation per effort varied depending on the condition. For example, in the F_L/P_N condition, subjects performed an average of 9.1 FI/min, comprised of an average of 5.8 efforts/FI and 123.9 degrees per effort. During the F_S/P_E condition, subjects performed an average of 7.5 FI/min, comprised of 7.5 efforts/FI and 95.9 degrees/effort.

The EMG data also offered interesting information about the FI task. There were differences in the within-subject COVs of the EMG when based on the average across each FI, versus the peak of each effort. Overall, the aEMG amplitudes were found to be more reliable. On the other hand, the peak aEMG amplitude of each effort was less consistent, contributing to higher within-subject COVs. This was likely due to the distinct actions that compose each FI. Each FI begins with the subject reaching and deviating the wrist to accommodate the orientation of the fastener. The fingers must then close around the fastener, adapting to its size and shape. During this time, the wrist and hand muscle activation would be increased to ensure enough force to start the task. Following the start of the task, the posture would be maintained for the most part, requiring only small adjustments in hand orientation to complete the task. Hence, deviations in EMG activation from the start of the task through to completion demonstrate large standard deviations, contributing to the large COV's.

Another interesting finding, related to aEMG was that the average across each FI was highly correlated with the peak from each effort, for most muscles. The Thenar was the only muscle monitored with an average correlation coefficient lower than 0.8 ($r = 0.75$)(Table 6). A possible explanation for this may be the functional role of the Thenar, and ultimately the thumb, during fastener initiations. Based on this correlation, it appears that all muscles except the Thenar contribute to stabilizing the joint and maintaining the required posture. On the other hand, Thenar muscle activity suggests that this muscle may be responsible for the motion required to perform a fastener initiation. Thus, because each effort varied from the one before, in terms of degrees of rotation per effort or velocity of each effort, changes in muscle activation patterns resulted. This is not the case for the other five muscles which exhibited a high correlation of FI determined EMG and effort determined FI. Discrete movements are not performed by these muscles as their primary role is to maintain joint position and stability during the FI task, such that variability is lower throughout each FI and peak and average become highly correlated.

Chapter 6

CONCLUSIONS

The kinematic data collected in the current study showed that, as posture changed from neutral to flexion to extension, a significant decrease in Fl/min resulted. This significant decrease in Fl/min also occurred from the large to the small fasteners. Based on these results, the condition that resulted in the highest frequency was F_L/P_N fastener (7.4 Fl/min) with the lowest occurring in the F_S/P_E condition (6.1 Fl/min).

Further analysis of the kinematic data showed that there were significant differences found in the duration of each Fl based on the posture and fastener sizes respectively. The duration data demonstrated that a greater amount of time was required to perform the Fl task when using the small fastener. Also, when subjects completed the Fl task in the three different postures a greater time was required during the P_E followed by the P_F and P_N respectively.

In addition, the kinematic data showed a significant increase in efforts/Fl when the combinations of posture and fastener size conditions deviated away from the F_L/P_N condition. This finding corresponds to the results reported above, where there was an inverse relationship between Fl/min and efforts/Fl, resulting in a relatively constant number of efforts per minute, across all conditions.

The EMG data collected during the current study showed that posture had a main effect on the results recorded from the BB, BR and Thenar muscles. The results showed that there were significantly lower EMG activities in the BB muscle when the task was performed in the flexion posture. Electrical activity of the BR muscle was found to be significantly higher during the P_E than when performing the Fl task in the P_N. Finally, the Thenar muscle displayed significantly higher EMG activation levels when the Fl task was performed in the P_E than when performing the task in the P_F.

A significant main effect of posture and a significant posture x fastener x age interaction was found in the FCU EMG data. Results from the 46-61 age group showed that during the F_L condition when in combination the flexion posture resulted in greater FCU EMG activity when compared to extension. In addition, when subjects were exposed to the F_S condition a significantly greater FCU EMG activity occurred in the P_F, compared to P_N and P_E. In the 31-45 age group, during the F_L, the P_E condition showed a greater FCU EMG activity level than the P_N condition.

The ECU displayed the greatest EMG activity of all six muscles recorded, regardless of the posture and fastener size combination. This result corresponded with Mogk and Keir (2003), where forearm extensor muscle activity was higher than in the flexors during a grip task performed at less than 50% MVE. Higher EMG activity of the ECU muscle has been associated with the force requirements needed for wrist joint stability. This muscle is constantly activated to ensure safety of the joint against both external and internal forces. In addition, the ECU EMG data displayed a significant main effect of posture and a significant posture x fastener size x age interaction. No significant differences were found in the data of the 46-61 or 31-45 age groups, however significant greater difference existed for the 20-30 age group, for the small fasteners where the ECU EMG amplitudes were greater for flexion than extension.

6.1 IMPLICATIONS TO INDUSTRY

The FI task was identified by professional Ergonomists, within the automotive industry, as posing a risk for injury to workers on the production line. Prior to this study, no guidelines or acceptable limits had been established for FIs. As a result, the purpose of the study was to determine acceptable levels of exposure for upper extremity rotations (including the forearm, wrist and fingers) while initiating fasteners for automotive assembly. Utilizing psychophysics, maximum acceptable initiation frequencies were determined for six combinations of three specific wrist postures: Neutral, Flexed and Extended and two fastener sizes (Large: 10 mm in depth and 20 mm in diameter; Small: 5 mm in depth and 10 mm in diameter) during repetitive low force (0.3 Nm) rotational exertions simulating those observed in industry.

The current study provided recommended TLV guidelines for acceptable frequencies of FIs per minute. These guidelines can be used to not only protect worker health and safety but also to ensure the quality of the vehicle. Proper installation of a fastener is essential to the function of the vehicle and to ensure this is possible, FI tasks must be designed within human capabilities to reduce the likelihood of an error occurring. For example, the recommended TLV's may help decrease errors such as stripped fasteners, overlooked fastener tasks and proper part installation.

Although most muscles involved in FIs had low activation levels, over time the cumulative effect of such activation, in combination with potentially hazardous postures, may lead to pain, discomfort or a repetitive strain injury. Known tasks with similar muscle activation patterns should be considered when allocating work on the assembly line. If a worker is required to perform FIs (activate the known muscle groups, through the associated rotational ranges) then other job elements should focus on alternate muscle group use. Thus, the EMG results of the current study can be used in combination with known data from other activities to effectively assign job elements.

The information obtained from this study is intended to be used by Ergonomists in industry to ensure that jobs involving FI tasks do not exceed the limit deemed acceptable to 75% of the female working population.

6.2 FUTURE RESEARCH DIRECTIONS

Future research should concentrate on accurately measuring and tracking the wrist and finger kinematics during the fastener initiation tasks. This would allow researchers to track the actual wrist movements to better explain the deviations in the EMG activity. Such a study would be able to provide information regarding specific postures that tend to lead to possible increases in the muscle electrical activity.

In regards to the psychophysical methodology, a research endeavor examining and validating the actual time requirements to train unskilled subjects to take on the role of a skilled worker is needed. Frequency and force based studies may require different lengths of time for subjects to be considered fully trained at a task. Another implication that could come out of such a study might be a decreased amount of participation time by each subject therefore allowing an increase in the number of total subjects recruited to partake in such a study, ultimately enhancing the overall power of the study.

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APPENDICIES

APPENDIX A

UNIVERSITY OF
WINDSOR
Office of Research Services

March 25, 2004 REB #04-039

Mr. Joel Cort
Department of Kinesiology
University of Windsor
Windsor, ON N9B 3P4

Dear Mr. Cort,

Subject: "A biomechanical and psychophysical examination of fastener initiations in automotive assembly"

This letter is in response to your application for ethics review at the University of Windsor. The University of Windsor Research Ethics Board (REB) has reviewed the above noted study. I am pleased to inform you that the proposal has been cleared by the Board for a period of one year.

As indicated in the *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans* you are required to do the following:

- Submit a Progress Report if your project extends beyond one year;
- Notify the REB when your project is completed;
- Submit a Request to Revise for any modifications to your project;
- Contact the Office of Research Services immediately regarding adverse events or unexpected events.

Forms for submission/notification to the REB are available at the Office of Research Services' Web Site: www.uwindsor.ca/research.

Please be sure that your supervisor completes and returns to the Research Ethics Coordinator the enclosed sheet to indicate when your project was completed.

We wish you every success in your research.

Maureen Muldoon

Maureen H. Muldoon, Ph.D.
Chair, University Research Ethics Board

cc: Dr. Jim Potvin, Department of Kinesiology
Linda Bunn, Research Ethics Coordinator

Enclosure

401 SUNSET · CHRYSLER HALL TOWER · WINDSOR ONTARIO · CANADA N9B 3P4
TELEPHONE: 519/253-3000 (3916) OR (3918) · FAX: 519/971-3667 · WEB: www.uwindsor.ca/research/ors

APPENDIX A

UNIVERSITY OF
WINDSOR

CONSENT TO PARTICIPATE IN RESEARCH

A Biomechanical and Psychophysical Examination of Fastener Initiations in Automotive Assembly

You are asked to participate in a research study conducted by: Dr. Jim Potvin and Joel Cort at the University of Windsor

If you have any questions or concerns about the research, please feel to contact either:
1. Dr. Jim Potvin, Associate Professor, Faculty of Human Kinetics, University of Windsor (253-3000 x2461; Room 117 HK Building; jpotvin@uwindsor.ca).

2. Joel Cort, Master's Degree Candidate, Faculty of Human Kinetics, University of Windsor (519-253-3000 x2468; Room 221 HK Building; cort@uwindsor.ca).

PURPOSE OF STUDY

The objective of this research is to establish acceptable exposure limits for manual fastener initiations used in automotive assembly facilities. Ford Motor Company has identified the need for a scientifically established threshold limit value for the manual initiation of fasteners in order to design work tasks as safely as possible. This study will use a psychophysical and biomechanical methodology to determine acceptable frequencies for repeated manual fastener initiations over an eight hour workday.

PROCEDURES

You will be asked to apply a rotational effort to rotate a fastener as many times as you deem acceptable within a one minute interval. Hand postures will be applied in the horizontal direction, relative to the body. Following a training period, you will be asked to apply efforts over various conditions representative of those found within traditional automotive facilities. These will be explained to you at the beginning of each session. You will be asked to exert effort levels for each condition as you perceive to be acceptable for a seven hour workday.

Conditions for data collection will include the application of an effort to provide industry standards for 2 sizes of fasteners: a) 10mm in depth and 20mm diameter and b) 5mm in depth and 10mm diameter. Three (3) postures will also be used during each fastener initiation. The wrist will be held in a neutral position, an extended posture as well as a flexed posture. The use of surface electromyography will be employed to aid in the measurement of muscle activity. Electrodes will be placed on the surface of your skin on the forearm and hand in order to measure muscle activity. These will be positioned by the researcher and can be easily removed at the end of each session

All conditions will be randomized for each participant. You will be instructed to adjust your effort levels to ensure comfort over an seven hour workday. Your ratings of perceived exertion will be recorded between each trial using Borg's Rating of Perceived Exertion (RPE) scale.

POTENTIAL RISKS AND DISCOMFORTS

The conditions and trials will occur within a fairly short time frame, and participants may experience some mild fatigue in the upper back, shoulder, arm and wrist. Muscle stiffness may result after the collection, but this should be no more than would be experienced after any unaccustomed physical activity.

POTENTIAL BENEFITS TO SUBJECTS AND/OR TO SOCIETY

Subjects will benefit from this study by gaining insight into Ergonomics research. In addition, this information will be used by Ford Motor Company to design workstations that are safer for the worker and yet provide a quality product.

PAYMENT FOR PARTICIPATION

A monetary fee of $15.00 (Canadian Currency) per hour of participation will be paid to those who are involved in the study. The total participation time for this study is expected to total 18 hours for a total of $ 270.00.

CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission. Only the researchers mentioned above will know your identity and personal information. This information will be stored in a secure computer in the ergonomics laboratory and will not be discussed or displayed in any form that would provide an indication of your identity.

PARTICIPATION AND WITHDRAWAL

You can choose whether to be in this study or not. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. You may exercise the option of removing your data from the study. You may also refuse to answer any questions you don't want to answer and still remain in the study. The investigator may withdraw you from this research if circumstances arise which warrant doing so.

FEEDBACK OF THE RESULTS OF THIS STUDY TO THE SUBJECTS

A summary of the findings from this study will be complied in a report that addresses the results and any conclusions and implications that result from the data. This report will be mailed to each of subject and subjects are encouraged to contact the researchers if there are any questions regarding the report.

SUBSEQUENT USE OF THE DATA

The data from this study will not be used in any form for future studies. Any data will be fully analysed and used in the conclusions of this study.

RIGHTS OF RESEARCH SUBJECTS

You may withdraw your consent at any time and discontinue participation without penalty. This study has been reviewed and received ethics clearance through the University of Windsor Research Ethics Board. If you have questions regarding your rights as a research subject, contact:

Research Ethics Co-ordinator
University of Windsor
Windsor, Ontario
N9B 3P4

Telephone: 519-253-3000, x 3916

SIGNATURE OF RESEARCH SUBJECT/LEGAL REPRESENTATIVE

I understand the information provided for the study "A Biomechanical and Psychophysical Examination of Fastener Initiations in Automotive Assembly" as described herein. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

____
Name of Subject

__________________________________ ____________
Signature of Subject Date

SIGNATURE OF INVESTIGATOR

In my judgement, the subject is voluntarily and knowingly giving informed consent to participate in this research study.

__________________________________ ____________
Signature of Investigator Date

APPENDIX A

UNIVERSITY OF
WINDSOR

SUBJECTS NEEDED

WHO CAN BE A SUBJECT?
If you are a female between the ages of 20 to 60 years old, you can participate in our study. Any candidate with a previous hand, wrist or shoulder injury will not be eligible to participate.

HOW LONG WILL IT TAKE?
Over a two week period, each participant will perform the experiment in the Ergonomics Laboratory located in room 207 of the Human Kinetics Building. The total number of hours of participation will be 18 hours over the 2 week period. Each session will last a maximum of 4 hours. Scheduling hours will be flexible. The study will begin March of 2004.

WHAT WILL YOU BE DOING?
This psychophysical and biomechanical based study is being conducted to develop repetition guidelines for the manual starting of bolts and fasteners in the automotive industry. You will be required to perform this task in 3 wrist postures (flexion, extension and neutral) used in industry. You will also be asked to determine repetition levels that would be acceptable to you over a seven hour work day.

WHO TO CONTACT?

Joel Cort
Faculty of Human Kinetics,
University of Windsor
Phone: 253-3000 ext.2468
Email: cort@uwindsor.ca,

Dr. Jim Potvin
Associate Professor
University of Windsor
253-3000 ext. 2461
jpotvin@uwindsor.ca

APPENDIX B

UNIVERSITY OF
WINDSOR

Subject Instructions

YOUR JOB IS TO MOVE THE FASTENER EVERY TIME YOU SEE THE WORD 'GO' ON THE COMPUTER SCREEN, AND TO ADJUST THE WORKLOAD ACCORDING TO THE GUIDELINES BELOW:

Rotate the fastener clockwise until you are given an auditory signal that you have completed the full 720 degree fastener initiation.

Only make contact with the fastener when you are performing a rotation.

You are permitted talk with each other, but *do not* talk about the experiment, or about how your hands, wrist and forearms are feeling.

You are not permitted to read, because we want you to concentrate on adjusting the work load.

We strongly encourage you to complete all movements during the day. We depend upon you for successful results, and greatly appreciate your participation.

Instruction for adjusting workload

We want you to imagine that you are on piecework getting paid for the amount of work that you do, but working a 7-hour shift that allows you to go home without unusual discomfort in the hands, wrists, or forearms.

In other words, we want you to work as hard as you can without straining your hand, wrist or forearm.

YOU WILL ADJUST YOUR OWN WORKLOAD. You will work only at the visual cues. *Your job will be to adjust the rate of repetition*; that is, to adjust the amount of rotations to complete the full 720 degrees.

Adjusting your own work load is not an easy task. Only *you* know how you feel.

IF YOU FEEL YOU ARE WORKING TOO HARD, adjust the pace that your hands are rotating.

HOWEVER, WE DON'T WANT YOU WORKING TOO LIGHTLY EITHER. If you feel that you can work harder, as you might on piecework, than increase your pace.

DON'T BE AFRAID TO MAKE ADJUSTMENTS. You have to make enough adjustments so that you get a good feeling for what is too hard and what is too easy. You can never make too many adjustments – but you can make too few.

REMEMBER... THIS IS NOT A CONTEST.

EVERYONE IS NOT EXPECTED TO DO THE SAME AMOUNT OF WORK.

WE WANT *YOUR* JUDGEMENT ON HOW HARD YOU CAN WORK WITHOUT DEVELOPING UNUSUAL DISCOMFORT IN THE HANDS, WRISTS, OR FOREARMS.

(Ciriello et al., 2002)

APPENDIX B

Upper Extremity Evaluation Scale (UEES) – Anterior Surface

Circle appropriate number for each column

Fingers & Thumb

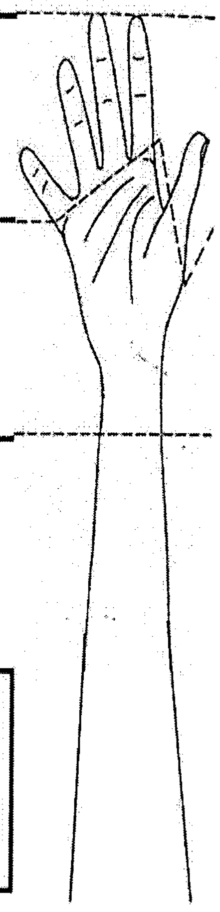
Soreness (Pain)	Stiffness	Numbness (Tingling)
0 = No Soreness	0 = No Stiffness	0 = No Numbness
1 = A little Sore	1 = A little Stiff	1 = A little Numb
2 = Somewhat Sore	2 = Somewhat Stiff	2 = Somewhat Numb
3 = Very Sore	3 = Very Stiff	3 = Very Numb

Hand & Wrist

Soreness (Pain)	Stiffness	Numbness (Tingling)
0 = No Soreness	0 = No Stiffness	0 = No Numbness
1 = A little Sore	1 = A little Stiff	1 = A little Numb
2 = Somewhat Sore	2 = Somewhat Stiff	2 = Somewhat Numb
3 = Very Sore	3 = Very Stiff	3 = Very Numb

Forearm & Elbow

Soreness (Pain)	Stiffness	Numbness (Tingling)
0 = No Soreness	0 = No Stiffness	0 = No Numbness
1 = A little Sore	1 = A little Stiff	1 = A little Numb
2 = Somewhat Sore	2 = Somewhat Stiff	2 = Somewhat Numb
3 = Very Sore	3 = Very Stiff	3 = Very Numb



Indicate location & discomfort type on drawing

So for Soreness

St for Stiffness

N for Numbness

Snook et al., 1995

APPENDIX B

Upper Extremity Evaluation Scale (UEES) – Posterior Surface

Circle appropriate number for each column

Fingers & Thumb

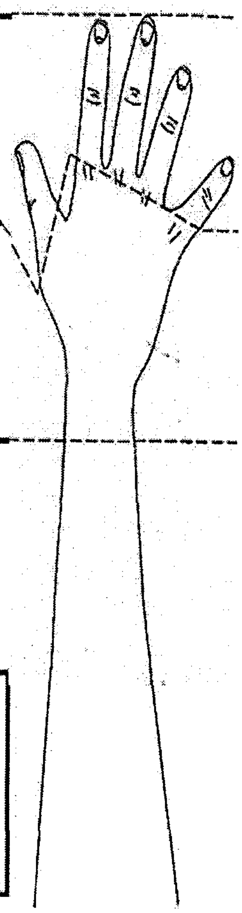
Soreness (Pain)	Stiffness	Numbness (Tingling)
0 = No Soreness	0 = No Stiffness	0 = No Numbness
1 = A little Sore	1 = A little Stiff	1 = A little Numb
2 = Somewhat Sore	2 = Somewhat Stiff	2 = Somewhat Numb
3 = Very Sore	3 = Very Stiff	3 = Very Numb

Hand & Wrist

Soreness (Pain)	Stiffness	Numbness (Tingling)
0 = No Soreness	0 = No Stiffness	0 = No Numbness
1 = A little Sore	1 = A little Stiff	1 = A little Numb
2 = Somewhat Sore	2 = Somewhat Stiff	2 = Somewhat Numb
3 = Very Sore	3 = Very Stiff	3 = Very Numb

Forearm & Elbow

Soreness (Pain)	Stiffness	Numbness (Tingling)
0 = No Soreness	0 = No Stiffness	0 = No Numbness
1 = A little Sore	1 = A little Stiff	1 = A little Numb
2 = Somewhat Sore	2 = Somewhat Stiff	2 = Somewhat Numb
3 = Very Sore	3 = Very Stiff	3 = Very Numb



Indicate location & discomfort type on drawing

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Snook et al., 1995

APPENDIX B

Medical Research Council Speech & Communication Unit

EDINBURGH HANDEDNESS INVENTORY

Surname.................................... Given Names....................................

Date of Birth.................................... Sex....................

Please indicate your preferences in the use of hands in the following activities *by putting + in the appropriate column.* Where the preference is so strong that you would never try to use the other hand unless absolutely forced to, *put* + +. If in any case you are really indifferent *put* + *in both columns.*

Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets.

Please try to answer all the questions, and only leave a blank if you have no experience at all of the object or task.

		LEFT	RIGHT
1	Writing		
2	Drawing		
3	Throwing		
4	Scissors		
5	Toothbrush		
6	Knife (without fork)		
7	Spoon		
8	Broom (upper hand)		
9	Striking Match (match)		
10	Opening box (lid)		
i	Which foot do you prefer to kick with?		
ii	Which eye do you use when using only one?		

L.Q.		Leave these spaces blank	DECILE	

MARCH 1970

APPENDIX B

UNIVERSITY OF WINDSOR

Subject Information Sheet

Subject Number	Subject Name

Address	
	City: Postal Code:
	Phone: W ( ) H ( )

Age	Height (m)	Weight (kg)

Handedness	Right
	Left

Have you ever experienced an Upper Extremity Injury?	Yes
	No

If Yes has been indicated please provide the date of the injury and any other specific details of the injury:

APPENDIX C

Kinematic Repeated Measures ANOVA Statistics

Fastener Initiations/minute			
Variable	**DF**	**F-value**	**P-value**
Age	2	0.675	0.5286
Fastener Size	1	28.885	<0.0001
Fastener Size x Age	2	0.323	0.7279
Posture	2	9.450	0.0004
Posture x Age	4	0.948	0.4459
Fastener Size x Posture	2	1.080	0.349
Fastener Size x Posture X Age	4	1.490	0.2225

Fastener Initiations Duration (s)			
Variable	**DF**	**F-value**	**P-value**
Age	2	2.400	0.1151
Fastener Size	1	22.141	0.0001
Fastener Size x Age	2	0.118	0.889
Posture	2	12.394	<0.0001
Posture x Age	4	0.520	0.7212
Fastener Size x Posture	2	1.754	0.1856
Fastener Size x Posture X Age	4	2.450	0.0608

Efforts/Fastener Initiation			
Variable	**DF**	**F-value**	**P-value**
Age	2	0.379	0.6892
Fastener Size	1	4.491	0.0462
Fastener Size x Age	2	0.239	0.7891
Posture	2	10.591	0.0002
Posture x Age	4	1.156	0.3437
Fastener Size x Posture	2	5.827	0.0058
Fastener Size x Posture X Age	4	0.371	0.8281

APPENDIX C

aEMG Repeated Measures ANOVA Statistics

aEMG Biceps Brachii			
Variable	DF	F-value	P-value
Age	2	2.390	0.1266
Fastener Size	1	0.536	0.4731
Fastener Size x Age	2	2.356	0.1219
Posture	2	6.509	0.0037
Posture x Age	4	1.270	0.2986
Fastener Size x Posture	2	0.190	0.8278
Fastener Size x Posture X Age	4	0.784	0.5428

aEMG Extensor Carpi Ulnaris			
Variable	DF	F-value	P-value
Age	2	0.540	0.5921
Fastener Size	1	0.182	0.6747
Fastener Size x Age	2	0.724	0.4982
Posture	2	0.473	0.6268
Posture x Age	4	0.694	0.6008
Fastener Size x Posture	2	0.318	0.7298
Fastener Size x Posture X Age	4	3028.000	0.0299

aEMG Brachioradialis			
Variable	DF	F-value	P-value
Age	2	3.352	0.0566
Fastener Size	1	0.472	0.5004
Fastener Size x Age	2	0.517	0.6045
Posture	2	4.632	0.0158
Posture x Age	4	1.058	0.3905
Fastener Size x Posture	2	0.591	0.5588
Fastener Size x Posture X Age	4	2.009	0.1128

aEMG First Doral Interosseous			
Variable	DF	F-value	P-value
Age	2	0.694	0.5116
Fastener Size	1	0.002	0.9653
Fastener Size x Age	2	0.341	0.7153
Posture	2	2.100	0.1365
Posture x Age	4	3.155	0.0247
Fastener Size x Posture	2	0.037	0.964
Fastener Size x Posture X Age	4	0.754	0.5615

aEMG Flexor Carpi Ulnaris			
Variable	DF	F-value	P-value
Age	2	2.156	0.1447
Fastener Size	1	0.110	0.7434
Fastener Size x Age	2	1.773	0.1982
Posture	2	3.981	0.0274
Posture x Age	4	1.142	0.3525
Fastener Size x Posture	2	0.105	0.9007
Fastener Size x Posture X Age	4	2.797	0.0404

aEMG Thenar			
Variable	DF	F-value	P-value
Age	2	3.167	0.0694
Fastener Size	1	1.802	0.1982
Fastener Size x Age	2	3.988	0.0393
Posture	2	3.529	0.0412
Posture x Age	4	0.925	0.4615
Fastener Size x Posture	2	0.493	0.6152
Fastener Size x Posture X Age	4	0.753	0.5636

APPENDIX C

pkEMG Repeated Measures ANOVA Statistics

pkEMG Biceps Brachii			
Variable	DF	F-value	P-value
Age	2	2.853	0.0825
Fastener Size	1	1.041	0.3204
Fastener Size x Age	2	1.944	0.1705
Posture	2	5.773	0.0065
Posture x Age	4	1.162	0.3427
Fastener Size x Posture	2	0.826	0.4456
Fastener Size x Posture X Age	4	0.512	0.7271

pkEMG Extensor Carpi Ulnaris			
Variable	DF	F-value	P-value
Age	2	2.478	0.1120
Fastener Size	1	0.123	0.7300
Fastener Size x Age	2	0.470	0.6325
Posture	2	4.113	0.0246
Posture x Age	4	1.231	0.3149
Fastener Size x Posture	2	1.224	0.3061
Fastener Size x Posture X Age	4	1.474	0.2303

pkEMG Brachioradialis			
Variable	DF	F-value	P-value
Age	2	3.983	0.0359
Fastener Size	1	0.341	0.5662
Fastener Size x Age	2	0.611	0.5531
Posture	2	4.625	0.0159
Posture x Age	4	0.641	0.6367
Fastener Size x Posture	2	0.767	0.4715
Fastener Size x Posture X Age	4	1.976	0.1178

pkEMG First Doral Interosseous			
Variable	DF	F-value	P-value
Age	2	0.168	0.8462
Fastener Size	1	1.380	0.2670
Fastener Size x Age	2	0.854	0.4414
Posture	2	2.883	0.0683
Posture x Age	4	2.731	0.0431
Fastener Size x Posture	2	0.378	0.6881
Fastener Size x Posture X Age	4	1.330	0.2765

pkEMG Flexor Carpi Ulnaris			
Variable	DF	F-value	P-value
Age	2	2.575	0.1039
Fastener Size	1	0.014	0.9069
Fastener Size x Age	2	0.367	0.698
Posture	2	9.035	0.0007
Posture x Age	4	2.083	0.1033
Fastener Size x Posture	2	0.064	0.9379
Fastener Size x Posture X Age	4	2.721	0.0446

pkEMG Thenar			
Variable	DF	F-value	P-value
Age	2	2.634	0.1026
Fastener Size	1	0.493	0.4928
Fastener Size x Age	2	0.595	0.5632
Posture	2	2.780	0.0770
Posture x Age	4	2.023	0.1147
Fastener Size x Posture	2	0.999	0.3795
Fastener Size x Posture X Age	4	1.247	0.3109

VITA AUCTORIS

Name:	Joel Aaron Cort
Place of Birth:	Hamilton, Ontario, Canada
Year of Birth:	1977
Education:	Sherwood Secondary School 1991 – 1994
	Bishop MacDonnell Secondary School 1994 – 1995
	Our Lady of Lourdes 1995 – 1997
	Wilfrid Laurier University 1997- 2001 Honours B.A. (Kinesiology & Physical Education)
	University of Windsor 2002 – 2004 M.H.K.