Strength Capabilities and Subjective Limits for Repetitive Manual Insertion Tasks

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(ABSTRACT)

This study is an investigation into methods of developing ergonomic guidelines for automotive assembly tasks involving insertion of small parts. The study was conducted in four major parts: 1) a method of determining and evaluating subjective exertion limits was modified and tested, 2) a large dataset was collected from an industrial population in 10 simulated assembly line tasks, 3) a smaller dataset was collected from a student population to assess hand dominance effects, and 4) strength data obtained was compared with a strength prediction model to determine if the model could predict manual insertion forces.

The traditional method of psychophysical data collection requires participants to extrapolate sensations from a relativity short session to judge if the task could be done for a much longer period. Maximum acceptable limits (MALs) are typically derived from having participants adjust a weight, resistance, or frequency to an acceptable level. The present study evaluated a relatively new method of collecting MAL data for simple, single-digit exertions where participants were asked to determine an MAL by self-adjusting and then regulating to maintain the exertion level. Results showed that MAL values obtained from a series of self-regulated exertions were independent of both analysis method and duration (5 minutes vs. 25 minutes) used for evaluation, and that the method was repeatable both within and between sessions.

Ergonomic guidelines are often obtained from the strength capacity for a certain task, as it is important to ensure that workers possess sufficient strength to accomplish a task. As task demands increase, however, a larger percentage of a worker's strength capability in required, and other factors, such as performance and worker comfort, tend to be compromised. In this work, both strength capacity and subjective limits were obtained for a variety of simulated tasks to facilitate development of guidelines for the specific tasks. The relationship between these two measures (maximum force, acceptable force) was determined, and acceptable limits were found to be approximately 55% of population strength capacity, with correlations (R^2) ranging from 0.40 to 0.60 depending on the task, suggesting the subjective limits and

strength capacity are related in these tasks. Hand dominance was found to have a small (5%), but significant ($p = 0.006$) effect on strength capability, and no significant effect on subjective limit.

Biomechanical strength prediction models can be used to assess loads placed on the human performing various tasks. One of the more popular models, Three-Dimensional Static Strength Prediction Program, is often used for heavy material handling tasks, such as lifting or pushing. The tasks studied presently, however, are manual insertions, requiring localized force application rather than whole body exertion. The prediction capabilities of this strength prediction model were compared with strength values obtained from the simulated assembly tasks. Results indicated that the model was not successful when predicting localized force, accounting for only 40% of the observed variance in strength ($R^2 = 0.4$)

This work is dedicated to the memory of my grandfathers:

Hal Johnson, whose life was full of success in both the business world and the community, and whose passing provided the financial encouragement for me to "go for it!", quit my job, and enroll in this graduate program.

Shannon Grayson, whose life taught me that book smarts are not the only thing you need to reach your dream and who taught me that my future was up to me.

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CHAPTER 1. INTRODUCTION

Overuse injuries are not a new problem. The first recorded overuse injury of the upper extremities was reported almost 300 years ago by the Italian physician Ramazzini. He documented injuries in a group of clerks who sat in constrained postures while they scribed (Habes, 1996). Occasional performance of hand intensive tasks around the home and workplace rarely results in problems, but frequent repetition of hand intensive tasks is suspected to lead to the development of overuse injuries. These injuries are thought to occur when various factors combine over time to increase the risk of damage. Some factors that have been identified as possibly increasing the risk of such injuries include high force, repetitive work, and extreme postures. The goal of this research was not to verify risk factors, but to investigate methods for determining limits on force levels in repetitive tasks.

Insurance companies, regulatory boards, and many employers are becoming increasingly aware of the potential for injury and illness that repetitive, hand intensive activities produce. Several states have issued ergonomic regulations in an attempt to reduce the incidence of ergonomic related injuries, often called work-related musculoskeletal disorders (WRMSDs). The Occupational Safety and Health Administration (OSHA) argued that WRMSDs are the "most prevalent, most expensive and most preventable" work-related injuries and illnesses in America, and therefore justified regulations to reduce their incidence (OSHA, 1999). They were, however, not successful as the first set of national ergonomic guidelines to reduce WRMSDs was issued late 2000, but was repealed shortly after via Congressional Review. These regulations would have covered many activities including lifting and pushing, with one focus on the prevention of upper extremity WRMSDs caused by hand intensive tasks. While these regulations will not go into effect, the attention given to ergonomic injuries demonstrated the need for study of tasks that may result in overuse injuries. Research in this area could support development of future guidelines and regulations.

In 1997, the National Institute for Occupational Safety and Health (NIOSH) issued a report on the epidemiological evidence for WRMSDs. It reviewed over 600 publications related to musculoskeletal disease of the hand, arm, elbow, shoulder, neck, and low back to determine epidemiological evidence of disease and to identity possible causal factors for such disease. For carpal tunnel syndrome and hand/wrist tendinitis, two WRMSDs of the distal upper extremities, their review suggested that evidence exists of positive correlations between both repetition and forceful work to the development of disease. Tendinitis was additionally correlated with deviated postures. The combination of all three factors, repetition, forceful work, and deviated postures, showed strong evidence of a positive correlation with development of a WRMSD (NIOSH, 1997).

Industrial tasks, such as lifting, have been studied for many years, and lifting research has lead to a successful reduction in work related back injuries (Snook, 1985). There is a need for similar research in the area of hand intensive tasks, in particular developing realistic limits for the factors identified as likely to cause WRMSDs of the hand and wrist. By measuring strength capabilities in a variety of realistic industrial postures, design recommendations can be made for similar tasks that are performed occasionally. For more repetitive tasks, derivation of acceptable limits, similar to what has been done in the area of lifting, may be useful in designing and setting guidelines for such tasks. This research studied both, by determining finger strength capabilities in a variety of postures and investigating acceptable limits using finger exertions for both trained and untrained experimental participants. Procedures for obtaining acceptable limits for such finger exertions were also investigated, and results were compared with an existing strength prediction model. Three specific hand couplings were selected for study: an index push, thumb push, and lateral pinch (key) push, as they comprise a large portion of insertions observed on assembly lines.

CHAPTER 2. LITERATURE REVIEW

2.1 Work-related musculoskeletal disorder incidence

Incident rates of WRMSDs appeared to grow over the past several decades, and now a large component of workplace illnesses is comprised of these disorders. WRMSDs of the upper extremity include carpal tunnel syndrome (CTS), tendinitis of the hand, wrist, elbow, and shoulder, rotator cuff injuries, along with a host of other identified occupational diseases. The rise in WRMSDs has become a concern for industry, and there has been a parallel increased effort to develop methods of prevention.

In 1998, the Bureau of Labor Statistics (BLS) found almost 65% of work-related illnesses were associated with repeated trauma (BLS, 1999a). Over the past 20 years, WRMSDs peaked in 1994 with an incidence rate of 41.1 per 10,000 workers. The rate dropped to 28.5 in 1998 and seems to have stabilized (BLS, 1999a). Considering CTS alone, the median time away from work in 1997 was 25 days while the overall median for work related injuries and illnesses was only 5 days (BLS, 1999b). Webster and Snook (1994) reported a nine-fold increase in the number of Workers Compensation claims related to repetitive stress between 1981 and 1991. By 1991, these claims accounted for 61% of all occupational illness, indicating a need for attention is this area, even though the costs associated with low back pain are still reported to be higher than all upper extremity WRMSDs (Webster and Snook, 1994).

While the increase in WRMSDs seems to be quite dramatic, there is some controversy over these numbers. Increased awareness of symptoms and avenues for compensation may account for some of this increase, as workers became aware they could receive compensation for what had previously been thought of as just normal aches and pains. Ireland (1998) discussed the repetitive strain injury phenomenon of Australia in the mid-1980's. Companies reported increases in repetitive strain injury incidence as high as 275% in one year. The largest increases in repetitive strain injuries were among low paid workers who were largely dissatisfied with their jobs. Ireland (1998) suggested that the power of suggestion, reinforced by outlets such as the media and labor unions, was largely responsible for this large increase. There are many similarities between Australian repetitive strain injuries and the American WRMSD increase in early 1990's (Ireland, 1998). It is likely that a large portion of the 900% increase reported by

Webster and Snook (1994) can be attributed to factors such as increased awareness and job dissatisfaction. Nonetheless, the prevalence and costs of upper extremity WRMSDs are clearly non-trivial and warrant attention towards preventive measures.

2.2 Risk factors and possible causes of work-related musculoskeletal disorders

Risk factors for upper extremity WRMSDs such as carpal tunnel syndrome and hand/wrist tendinitis include high force exertions and frequent repetition. Extreme deviated postures alone have not been shown conclusively to lead to development of a WRMSD. When these factors exist in combination, though, the strongest evidence for an increased risk of WRMSD development occurs (NIOSH, 1997).

One WRMSD that has received considerable attention among researchers is carpal tunnel syndrome. A likely cause of carpal tunnel syndrome is excess pressure development in the carpal tunnel and subsequent impact on median nerve function (Armstrong and Chaffin, 1979a). With the wrist in a neutral position, normal resting pressure in the carpal tunnel is about 5 mmHg, but this pressure will increase ten-fold when a load is applied to or by the fingertip (NIOSH, 1997). Many industrial tasks involve forceful insertion of small parts, efforts that are frequently accomplished with the fingers or thumb. Using stress, strain, and the viscoelastic properties of tendons, Miller and Freivalds (1995) determined that the stress on the tendons was higher in wrist extension than flexion and that grasps are safer than pinch grips. Wrist extension has also been found to pull the median nerve taut and reduce the volume in the carpal tunnel (Armstrong and Chaffin, 1979b). Combining the high forces applied to the fingertips during industrial insertion tasks with the added stress produced on the tendons from a deviated posture creates a high risk for development of carpal tunnel syndrome or another WRMSD (NIOSH, 1997).

2.3 Hand strength capabilities

Hand grip strength is considered one of the common indices of human muscle strength (Ohtsuki, 1981). Grip strength has been studied extensively, but there have been relatively few studies on the force capabilities of individual fingers. Strength capability of the fingers is needed for the design of industrial tasks that require finger force. For example, many assembly tasks require forces to be applied by a single digit. Observations on an assembly line show that workers inserting parts such as fasteners tend to use their thumb, index finger, middle finger, or a combination of the index and middle fingers. Other factors, such as gender and posture, may influence strength capability for such tasks. Knowledge of individual finger strength could be used in the design of industrial tasks to decrease the risk of injury to the majority of the population.

Ohtsuki (1981) showed that the middle and index finger tend to be the strongest, by measuring grip strength and subsequently determining the percent contribution of each digit. It was also found that the middle finger supplied the most force in grip efforts, followed closely by the index finger. Radwin and Oh (1992) found the ring and little finger combined to account for only about one-third of total force in grip strength testing, confirming that the majority of grip force is generated by the index and middle fingers.

Pinch grip has also been studied as a measure of hand and finger strength. Radwin and Oh (1992) found that in pinch grips using all digits, the index finger generated more force than the middle finger, providing 35% and 26% of total pinch strength respectively. Mathiowetz et al. (1985) investigated grip and pinch forces for 628 participants. While individual digit strength was not investigated, several useful recommendations were made for obtaining reliable hand strength data. They found that the average of three maximum trials was the most reliable method of measurement. Additionally, they recommend utilizing standardized postures and instructions for strength data collection (Mathiowetz et al., 1985). By standardizing postures and instructions, possible confounds were removed, increasing reliability and validity along with allowing comparisons with future studies, which could not be accomplished if posture was not standardized. Their data, however, were intended for use by physical therapists and doctors to benchmark the progress of injured patients, and the recommendations may therefore have little applicability to strength testing for industrial task design as industrial tasks do not conform to the rigid postures recommended.

Jones (1998) investigated the ability to produce a given finger force using haptic and visual feedback and haptic feedback alone. Subjects were asked to give maximum exertions during finger flexion, and were then asked to maintain a given force for two minutes using the two feedback conditions. Using only tactile and haptic feedback, the force of 2, 4, or 6 Newtons was maintained with about 3%, 13%, and 5% error respectively. It was not clear if feedback presentation was balanced between subjects, since presentation of the visual feedback condition first could provide practice as to the tactile sensation and may affect the haptic only condition. The key finding is that participants appear to be able to self-regulate force exertions and maintain a given exertion level without external stimulus.

Astin (1999) investigated finger strength using a pinch gauge in various positions to measure single digit forces in a variety of couplings. The study provided a large data set of index finger strengths, though in only a neutral posture. Previous studies have also focused on only neutral postures, yet in general, strength varies as postures deviate from neutral (e.g. Chaffin and Andersson, 1991). This reduces the applicability of studies conducted with only a neutral posture, since most industrial tasks require a force to be applied from non-neutral postures. A task designed with neutral posture data risks significant errors due to changes in capability resulting from different postures or force directions. By closely simulating actual postures seen in industry, a data set could be developed that is more applicable to the evaluation of current and future industrial tasks.

2.4 Applying strength data to task design

One major drawback to existing data on hand strength capabilities is the lack of applicability to industrial task design. Studies generally are conducted using specific postures and data collected in a laboratory setting. Few industrial tasks utilize these standardized postures, instead workers are free to move and adjust their posture to best perform the task and to be most comfortable. Additionally, these studies have not been adapted to produce many empirical guidelines to be used in task design. Common methods to apply strength data to repetitive task design are provided the American Conference of Governmental Industrial Hygienists (ACGIH, 2001) by Kodak (Eastman Kodak, 1986).

The ACGIH developed a guideline for use in hand intensive activities. This guideline includes both a threshold limit value (TLV), which should never be exceeded, and an action limit, which indicated administrative controls, such as monitoring, should be employed. To use this guideline, a hand activity level (HAL) is first defined on a ten-point scale. A typical HAL seen on assembly lines is two. This value corresponds to an exertion every four to eight seconds or 'short bursts of hand activity' (ACGIH, 2000). The second value needed to evaluate a task with the TLV is a normalized peak force. This value is the percent of mean strength capability that is needed for the task, and is also normalized to a ten-point scale. Both the TLV and the action limit are obtained via cross-referencing the HAL with a graph (Figure 1). For the example hand activity level of two, the normalized peak force for the TLV is six, and four and a half for the action limit. That is, if the task requires more than 60% of the worker's strength capacity, the task is above the TLV. Table 1 shows this action limit applied to several studies on single digit strength capabilities.

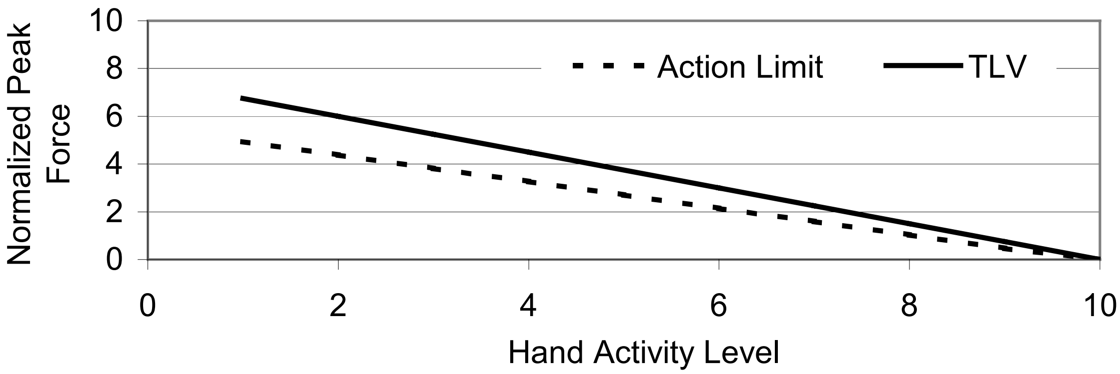

Figure 1. ACGIH Hand Activity TLV (adapted from ACGIH, 2000)

Another method of designing tasks is to start from strength capability data and design a task to meet the strength capability of the majority of the population. This method would ensure that most workers could perform a task, but it does not necessarily guarantee a worker could do the task repeatedly without risk of illness. Kodak recommended using 20% of the strength capacity of 'weaker workers' as a design guideline in repetitive tasks (Eastman Kodak, 1986). Table 1 shows this 20% rule applied to the same set of studies on single-digit strength capabilities. Values of the 10^{th} percentile were used to represent weaker workers. From Table 1 it can be seen that the two guidelines produced vastly different forces, with force limits from ACGIH guidelines 225% to 700% greater than those obtained from the Kodak guidelines. Also, the selection of specific strength data to be used can greatly affect the force limit, as similar tasks vary across the studies. It is not currently known which, if either, of these guidelines is better for designing tasks.

Table 1. Comparison of several studies with tasks similar to those being investigated (all values in Newtons).

		Mean	Std Dev	5th Percentile	20% of 10th Percentile (Kodak)	Normalized Peak Force at ACGIH Action Limit
Schoorlemmer and Kanis (1992) [1]						
Thumb Push (free posture)	Male	86.9	43.0	16.0	6.3	39.1
	Female	68.5	36.1	8.9	4.4	30.8
Thumb Push (90° elbow flexion)	Male	81.3	26.7	37.2	9.4	36.6
	Female	64.1	32.4	10.6	4.5	28.8
Astin (1999) [1]						
Index-Finger Push (forward)	Male	52.6	18.0	22.9	5.9	23.7
	Female	39.3	14.9	14.7	4.0	17.7
Index-Finger Press (down)	Male	50.9	18.4	20.6	5.4	22.9
	Female	35.2	14.9	10.6	3.2	15.8
Hertzberg (1973)						
Thumb Push	Male	77.4	16.7	49.9	11.2	34.8
Index Push	Male	56.8	12.7	35.8	8.1	25.6
Dickson (1972) [2]						
Index Push (Dominant)	Male	45.1			9.0 [3]	20.3
Index Push (Non-dominant)	Male	43.1			8.6 [3]	19.4
Army (MIL-STD-1472D) [4]						
Grip Push (up)	Male			98.0	19.6 [5]	n/a[6]

[1] Participants were seated
[2] Only 50th percentile male were reported
[3] Values represent 20% of the mean
[4] Only 5th percentile male were reported
[5] Values represent 20% of the 5th percentile
[6] Mean was not provided, cannot be calculated

2.5 Psychophysical data collection

Psychophysics is the study of the relationship between a physical stimulus and the associated sensory response. The study of psychophysics began in the later part of the nineteenth century with Weber's Law, which states that the ratio of a just noticeable difference and the stimulus intensity is constant. Early psychophysical research focused on determining the constant values for various types of stimuli. Further investigation in Weber's law resulted in

Stevens' power law, published in 1960, which demonstrated the relationship between strength of sensation versus stimulus intensity (Krawczyk, 1996). This power law is given by $S = kIn$, where S is sensation, I is stimulus intensity, k is a constant, and n is the slope of the line plotted in log-log coordinates. The value of n has been investigated for many stimuli and is approximately 1.6 for both muscle effort and force generation (Snook, 1985). This traditional definition of psychophysics has been expanded upon in the realm of industrial ergonomics, and is now often used to describe not only the physical stimulus and sensory response, but also a participant's perception of the physical stimulus.

The psychophysical method of determining a maximum acceptable weight of lift (MAWL) was first published by Snook and Irvine (1967), and has been modified, improved upon, and used extensively for the past 30 years. The method involves instructing participants to imagine they are doing a task for a set period and then perform the task for a fraction of the imagined time. Participants are typically given control over one task variable and allowed to adjust that variable to a comfort level (Snook, 1985). For example, in a lifting task, the adjustment method may be adding and removing water or lead shot. This method of adjusting forces involves more than just the traditional psychophysical idea of sensation and response, but also requires the participant to make a perceptual judgment of force, as the participant must then extrapolate sensations to estimate if the task could be done for a set period. Snook and Irvine (1967) first used a one-hour time-period to estimate a maximum acceptable frequency of lift for an 8-hour period. It is now accepted that a 20 to 25 minute adjustment period can be used to determine 8-hour capacity with reasonable accuracy (e.g. Snook, 1978; Legg and Myles, 1981; Mital, 1983; Karwowski and Yates, 1984).

Legg and Myles (1981) tested the validity of a subjective method for determining MAWLs using military participants. Soldiers were given 10, 20-minute periods over the course of five days to adjust their load. The average of the 10 testing sessions was used for the participants' MAWL. Later, participants returned to the lab where they then lifted the averaged MAWL for eight hours. Physiological measures of fatigue were collected, including heart rate and oxygen consumption, and subjective ratings of fatigue were rated using a 20-point scale. Heart rate during the 8-hour period averaged 92 beats per minute, while average energy expenditure was 21% of VO_2 max. Both these values are within the limits of physical activity for an 8-hour day. Subjective ratings averaged 11.4, which is associated with "fairly light" work.

The authors concluded that the psychophysical methods were able to determine an MAWL that would not cause undue fatigue. This study used a motivated and physically fit soldier population; it is not clear if a similar study on typical industrial workers would produce comparable results.

Mital (1983) studied the validity of the psychophysical method for determining MAWL in industrial workers. Ten physically fit industrial workers estimated an 8-hour MAWL during a 25-minute adjustment period. They were then asked to "imagine" working a 4-hour overtime shift, and were given an additional 20-minute adjustment period to determine a 12-hour MAWL. Four frequencies of lift were used: 1, 4, 8, and 12 lifts per minute. Both physiological and psychophysical measures of fatigue were obtained in a second session, in which the participants then lifted their MAWL for an 8-hour or 12-hour day. Additional adjustments were allowed during the second session. Males on average lifted only 65% of their estimated 8-hour MAWL, while females were able to lift 85%. For the 12-hour shift, males and females lifted 61% and 77% respectively. Frequencies of 1, 4, 8, and 12 lifts per minute were used, however the results were not reported with respect to frequency (Mital, 1983). It is difficult to discern if the significant difference found in weight over time is true for all frequencies, or if this study merely confirms others (e.g. Ciriello and Snook, 1983; Karwowski and Yates, 1986) that found the psychophysical method produces over estimates of MAWL at high frequencies.

The difference between trained industrial workers and inexperienced student volunteers when determining MAWL was investigated by Mital (1987). Student MAWL values differed significantly from industrial workers, but the students were more accurate at estimating their MAWL than trained workers. Male students estimated 8-hour MAWLs that were 11% lower than industrial workers were, while 12-hour MAWLs were only 2% lower. Females' 8-hour and 12-hour MAWLs were lower by 6% and 2% respectively. While this study shows that inexperienced participants can accurately determine an MAWL, it also suggests that experimental populations should match the desired population to produce accurate estimates using psychophysical methods.

Karwowski and Yates (1986) compared several existing studies using the psychophysical method to estimate MAWL, and obtained new MAWLs to evaluate reliability. At high frequencies, such as 6, 8, 9, and 12 lifts per minute, MAWLs were not reproducible across studies. They also noted the metabolic demand resulting from lifting the selected MAWL for the entire work shift would exceed the recommended heart rate for most workers. This lead to the conclusion that participants were likely cueing from muscle fatigue rather than estimating metabolic demands, and that the method does not produce reliable results at such frequencies.

2.6 Upper extremity psychophysical research

Much research has been performed to identify possible causal factors for upper extremity WRMSDs. Little, however, is known currently regarding quantitative limits for these factors. Objective quantitative limits could aid in a reduction in WRMSD incidence rates. Snook (1985) compared back injury records over several years to MAWL studies, and noted that consideration of psychophysical limits in the design of lifting tasks has the potential to reduce back injuries by as much as one-third. It is reasonable to expect that similar application of psychophysical methods to hand intensive activities, such as those seen on an assembly line, would have similar results.

Psychophysical methods have been used for many years to analyze whole body exertions such as lifting and pushing. Over the past decade, there has been an emergence of psychophysical research directed toward the upper extremities. Fernandez et al. (1995) reviewed several unpublished thesis and dissertations relating to psychophysical applications of maximum acceptable frequencies (MAF) and the upper extremities. In each of these studies, participants were asked to maintain a certain percent of their maximum voluntary contraction and arrive at an MAF at which they would be comfortable with the task for 8-hours. It was noted that as force and duration increased, MAF generally decreased for both gripping and pinching tasks.

Several studies have been conducted to determine maximum acceptable force limits (MAL) in repetitive wrist flexion and extension (Snook et al. 1995, 1997, 1999). These studies all used a magnetic brake system which participants adjusted to arrive at their MAL. Participants were encouraged to adjust the brake as often as they wished. All three cited studies differed from previous psychophysical MAL studies because they did not have 20-minute adjustment period. Instead, participants actually used the magnetic brake system to adjust resistance for several 8-hour days. Participants were asked daily about possible WRMSD symptoms and those that displayed symptoms were removed from the study. The limits that were reported were those that did not produce significant symptoms of WRMSDs over a period of several weeks. No follow-up was reported to determine if symptoms appeared in the time following the study, nor was it reported how the resistance selected daily changed over the course of the study.

2.7 Strength Prediction

Biomechanical models can be used to assess potential hazards placed on the human while performing tasks. Chaffin and Andersson (1991) argue that the use of such models is more than just academic, and that models can be used to evaluate and identify loads that may be hazardous to workers. Several such models have been developed for whole body tasks, as well as a variety of models for hand and wrist biomechanics and discomfort (Armstrong and Chaffin, 1979a; Lin and Radwin, 1997).

One strength prediction model that is often used is The University of Michigan's 3D Static Strength Prediction Program ™ (3DSSPP), developed using a large strength database obtained over a 25-year period (University of Michigan, 1998). Verification of the model by Chaffin and Erig (1991), with data obtained from 29 males performing one lift and three push/pull tasks, revealed that the model was extremely sensitive to variations in posture, but was reasonably successful in predicting mean population strength. This software is often used alone, or in combination with other tools such as the NIOSH Work Practices Guide for Manual Lifting (NIOSH, 1991), to assess low back risk to workers.

The hand and wrist model developed by Armstrong and Chaffin (1979a) is limited to predicted stress and strain on the ligaments and tendons, and does little to predict strength capability. Similarly, Lin and Radwin's (1997) model only predicts discomfort at a given exertion level, frequency, and angle of wrist deviation. The model could be inverted with acceptable limits obtained, selecting an acceptable discomfort level and predicting the force levels. This model is only applicable to task that require wrist deviation, and is therefore not applicable to the present study. Eksioglu, Fernandez, and Twomey (1996) used both artificial neural networks (ANN) and statistical models to predict peak pinch strength from a variety of factors, such as elbow and shoulder flexion, age, weight, grip strength, and various arm and hand dimensions. They found that the ANN model better predicted peak pinch strength than statistical models. Each of these models may be useful for the situation in which they were developed, but they cannot be easily translated to other situations and tasks. Given the popular application of

3DSSPP, however, and its apparent ability to predict mean population strength, it is of interest and potential utility to determine whether it can be used to predict manual insertion strengths.

CHAPTER 3. RESEARCH OBJECTIVES

3.1 Purpose

This research focuses on the determination of strength capabilities in simulated industrial insertion tasks and the associated acceptable limits for those tasks. A method of determining the acceptable limits was investigated. Tasks were selected from typical assembly line tasks, in order to produce data more applicable for future task design. The results were used for design at a large automobile manufacturer, and may be generalized to similar industrial tasks. Additionally, the methods used for determining psychophysical limits are relevant for future research on developing a range of ergonomic guidelines.

3.2 Motivation

Most existing research on hand strength limitations has focused on grip and pinch strength. A small portion have investigated finger strength, but only in a neutral posture, and none have simulated actual industrial tasks. Neutral postures are not common in industry, which somewhat limits the applicability of this prior research. A need exists to investigate strength capabilities in tasks that closely resemble industrial tasks. Data such as these will allow for better design and evaluation of tasks. Knowledge of the relationship of posture, coupling, and hand dominance on strength capability may be used in prediction of single digit forces. The ability to predict force capabilities without needing to collect data would make the design process faster and easier.

Psychophysical research for determining maximum acceptable limits traditionally requires participants to adjust a weight, force, or frequency to an acceptable level. There is typically an external source to assist in maintaining the exertion level, such as a metronome for frequency or a weighted box for lifting. In the present work on hand and finger exertions, once an acceptable limit has been reached, the participants were expected to self-regulate that level on their own without the assistance of any external stimuli. Jones (1998) found that participants were able to reproduce hand forces with reasonable accuracy without the aid of external stimulus, leading to the hypothesis that participants will be able to maintain a given force level once it is reached.

The current accepted adjustment period for psychophysical determination of acceptable limits is 20 to 25 minutes for an 8-hour estimate. Reducing the MAL adjustment period could lower experimental costs using these methods. Data collection with a self-regulation method may lead to a reduction in MAL determination time, and it may reduce the mental workload associated with transferring sensations to physical adjustments. Additionally, a work shift of eight hours is often assumed. Reducing the imagined work shift may also reduce the time needed for estimation. Many assembly lines now incorporate job rotation, so workers spend two to four hours on a single task. A full 25-minute session therefore may not be needed for such work shifts.

3.3 Objectives

This thesis focuses on simple pushes with the index finger, thumb, and a lateral pinch. Methods of psychophysically determining acceptable forces were explored along with force capabilities of the digits in push tasks. Based on the motivations for this research, several objectives were determined:

- Establish methods of evaluation and time dependency for a series of force data obtained using a self-regulation psychophysical method.
- Determine the reliability and interrelations of MAL and MVE measures for hand intensive tasks.
- Quantify the effects of individual differences and occupational factors on force capabilities and acceptable limits in hand intensive tasks.
- Determine predictability of the index finger and thumb force capability based on individual differences and occupational factors using an existing strength prediction model.

Identification of possible relationships between MVE and MAL measures would facilitate future research by limiting the need for MAL evaluation, by instead applying a correction to the MVE to estimate an MAL. In situations where a correction may not be applicable, the self-regulation method of determining an MAL estimate may be preferable to the traditional, external regulation method. Possible correlations between the individual or occupational factors, found with regression models or existing strength prediction models, could further facilitate the design of industrial tasks by eliminating the need to collect experimental data.

The objectives were accomplished with two studies conducted at Virginia Tech, and a third conducted on location at a large U.S. automobile manufacturing plant. These data were then compared against strength values obtained from 3DSSPP, an accepted strength prediction model.

CHAPTER 4. INVESTIGATION OF MAL EVALUATION METHODS

4.1 Overview

The traditional method of psychophysical data collection, developed by Snook (1967), requires participants to extrapolate sensations from a relativity short session to judge if the task could be done for a much longer period. Maximum acceptable limits (MALs) are typically derived from having participants adjust a weight, resistance, or frequency to an acceptable level. For example, weighted boxes have been used for lifting tasks (e.g. Snook and Irvine, 1967; Karwowski and Yates, 1986), and magnetic breaks or pneumatic pressure devices (e.g. Snook et al, 1997, Potvin et al, 2000) for upper extremity exertions. The present study evaluated a relatively new method of collecting MAL data for simple, single-digit exertions. Instead of an external control on exertions, participants were asked to determine an MAL by self-adjusting and then regulating to maintain the exertion level. This self-adjust and regulate method differs from previous MAL studies and was evaluated in terms of repeatability. Methods of analysis also needed to be determined to allow for extraction of a single MAL from a sequence of exertions.

Jones's (1998) study suggested that a given force level can be maintained once it is reached. It was therefore hypothesized that participants could be instructed in a similar method as previous psychophysical research, and with the additional instruction to simply press as hard as they felt they could for up to a two-hour shift. That is, participants would be able to self-adjust and self-regulate their force exertions to a consistent level, thereby selecting their MAL. Figure 2 shows a sample 25-minute trial in which the participant was asked to use the self-adjustment method. While an MAL could be "eyeballed" from the sequence of individual exertions, a formal method was desired to produce repeatable results that avoided experimenter bias. The data appeared to resemble a noisy signal that converges on a stable level after several minutes. Preliminary analysis led to two alternate hypotheses: the most stable period contains the MAL or the value at the end of the trial is the MAL. Methods of quantifying MALs from the series of discrete exertions were then developed from these two hypotheses.

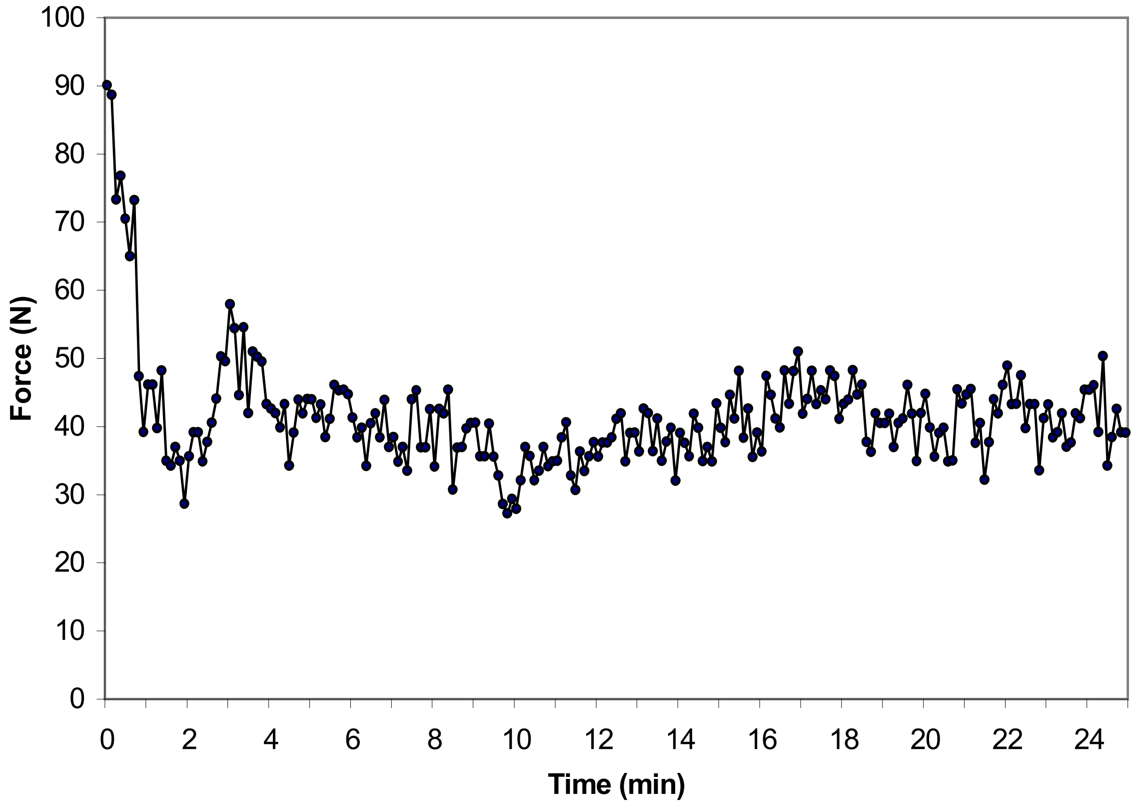

Figure 2. Representative data obtained during 25-minute MAL Session. Peak values are shown for exertions performed nine times per minute.

The first hypothesis assumes that the participant stabilizes around a value and further that this stable value is the MAL. In Figure 2, there are several "flat" sections, each of which could be considered as an MAL estimate. Under this hypothesis, however, the longest of these stable periods likely represents the force the participant selected as the MAL. An analysis method was developed which focused on the longest window of data with the smallest standard deviation, and then reported the mean within the window. This method was referred to as minimizing the standard deviation (MSD).

The second hypothesis is more closely related to previous lifting research, where the final weight of the lifted box was used, however it requires finding an end value. There is likely some error contained in the final exertions due to inherent variability in a series of exertions. Two methods were identified to represent this hypothesis. First, it could be assumed that the exertions during the final minute varied around the MAL value, and an MAL value could be obtained simply by averaging the data obtained in the last minute of data collection. This method was called the last minute average (LMA). Second, the MAL adjustment period could be seen as a noisy signal converging on an end value. The noise can be filtered out with a low-pass filter, the signal viewed as the MAL estimation curve, and the final value taken as the MAL the participant wished to convey. This final approach was called the Filter method for this research.

An additional goal of this study was to determine if repeatable MALs could be obtained with a shorter experimental session than is traditional. In the study described below, participants used a self-adjusting method during several 25-minute MAL estimation trials. Each trial was analyzed using the three analysis methods described above. In addition, two durations of exertion data were investigated to determine if a shorter adjustment period would produce consistent, repeatable MAL estimates.

4.2 Design

A three factor, mixed design with two sessions was used. The between subject factor was digit used with two levels [index finger (I) and thumb (T)]. Videotape observations were made of an automobile assembly line to select appropriate frequencies for the tasks studied. Frequency and session were within subject factors with three (3/min, 6/min, and 9/min) and two (first and second) levels respectively. Frequency presentation order was balanced with repeated latin squares (Table 2), while digit presentation order was counterbalanced (Table 3).

Participants were asked to judge forces in terms of a 2-hour work shift instead of the typical 8-hour workday, to represent job rotation that is becoming more prevalent in industry. Each MAL estimation period lasted 25 minutes, in which 75, 150, or 225 discrete exertions were performed.

Table 2. Latin square used for frequency balancing

Order	Frequency (presses per min)		
1	3	6	9
2	6	9	3
3	9	3	6
4	9	6	3
5	3	9	6
6	6	3	9

Table 3. Experimental Design for MAL data collection evaluation for the thumb (T) and index (I) finger.

Subject	MVE Digit 1	MVE Digit 2	MAL Digit	Order
1	T	I	I	1
2	T	I	I	2
3	T	I	I	3
4	I	T	I	4
5	I	T	I	5
6	I	T	I	6
7	T	I	T	1
8	T	I	T	2
9	T	I	T	3
10	I	T	T	4
11	I	T	T	5
12	I	T	T	6
13	T	I	I	1
14	T	I	I	2
15	T	I	I	3
16	I	T	I	4
17	I	T	I	5
18	I	T	I	6
19	T	I	T	1
20	T	I	T	2
21	T	I	T	3
22	I	T	T	4
23	I	T	T	5
24	I	T	T	6

4.3 Participants

Participants were recruited from the student population at Virginia Tech. Each participant completed an informed consent procedure approved by the Institutional Review Board of Virginia Tech (IRB #00-217) and was compensated at a nominal rate for their time. There were 24 total participants (14 male, 10 female), and all were right handed. Sample size was consistent with previous studies, which ranged in size from 7 to 24 participants (Ciriello and Snook, 1983; Karwowski and Yates, 1986; Snook, 1985; Snook et al., 1995; Snook et al, 1999). Ages ranged from 18 to 31 (mean = 22). Three participants listed previous experience in a manufacturing environment ranging in time from two months to two years.

Anthropometric measurements were taken with participants' shoes removed and wearing everyday clothing. Participants had mean (sd) stature and body mass of 141.4 (8.6) cm and 73.6

(18.4) kg respectively. Standing shoulder height was measured from the floor to the acromion with mean (sd) of 143.3 (8.6) cm. Upper arm length, measured from acromion to medial epicondyle with the arm abducted and elbow at 90 degrees flexion, had mean (sd) of 29.0 (2.2) cm. Lower arm length, measured from medial epicondyle to wrist fold, had mean (sd) of 25.8 (1.7) cm.

4.4 Equipment

Force data were collected with a three-axis load cell (AMTI model MSA-6-500) and sampled at 60 Hz with LabVIEW^{tm} software. A piece of thick card-stock with the center marked was attached to the force transducer. The transducer was mounted to an adjustable table, allowing each participant to position the transducer to a comfortable level at approximately waist height.

4.5 Procedure

Postures were fixed, with participants standing and using their dominant hand to apply force vertically to the force transducer with the distal pad of the selected digit (Figure 3). Three maximum voluntary exertions (MVEs) were performed with the index finger and the thumb, and the maximum value across each set of exertions was recorded as the participants MVE. The traditional 'Caldwell regime' (Caldwell et al., 1974), which requires a total of five seconds for a "ramp-up, hold, ramp-down" cycle for MVE measurement, was modified to better represent the desired tasks. Participants were simply instructed to press in a controlled manner, vertically, at the center of the load cell. Each MVE trial was three seconds in length, with exertions lasting one to two seconds (e.g. Figure 4). Fz represented the force normal (perpendicular) to the plane of the transducer, which was the direction of concern. Specific attention was paid to forces parallel to the plane of the transducer surface (Fx and Fy). If these forces were above approximately 5% of the normal force, the participant was reminded to press straight into the transducer. In an ideal trial, the resultant force will equal the force in the Z direction (Fz) and the two sets of values will be nearly identical, as in Figure 4. A minimum of two minutes of rest was allowed between trials, consistent with Caldwell et al. (1974).

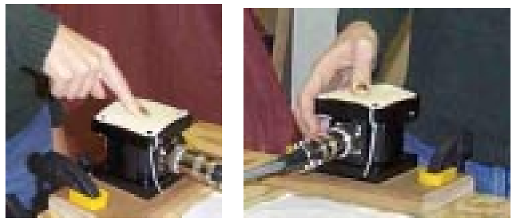

Figure 3. Examples of digit posture during index finger (left) and thumb exertions

Note: Participants were monitored to ensure they did not touch the transducer other than with digit being tested.

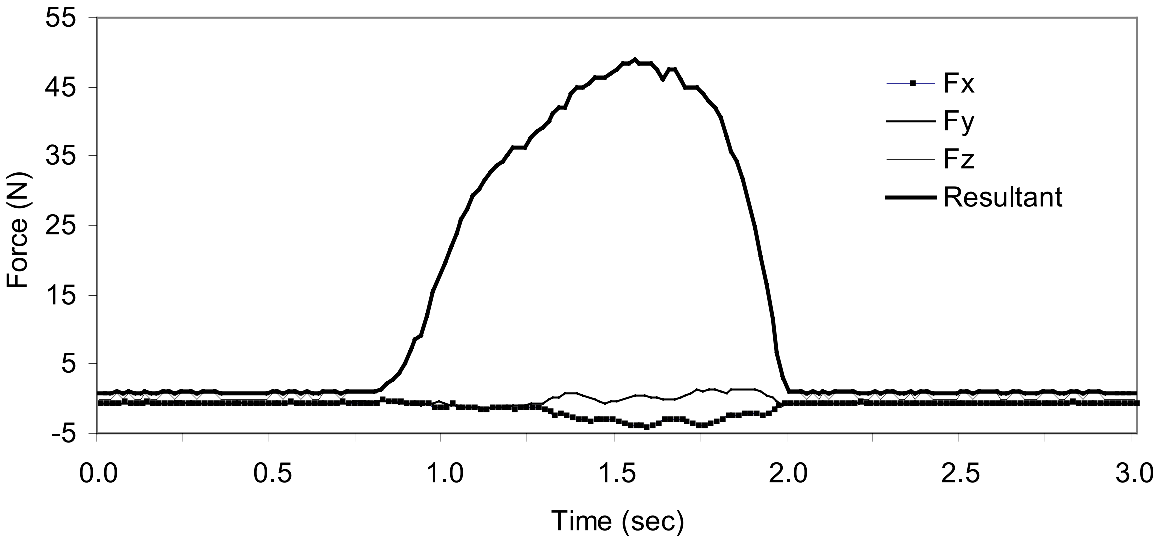

Figure 4. Sample index finger MVE trial

Few of the participants had manufacturing experience; therefore, a short video of typical assembly line processing involving inserting small parts with the fingers was shown to familiarize participants with the context of the study. Following the MVE trials and video familiarization, an MAL was described to be the force with which the participant could press at the given frequency without developing unusual discomfort, pain, numbness, or sensing an increased risk of injury in the finger, hand, wrist, forearm, or shoulder during a two-hour work shift. Participants were instructed that once an acceptable force was reached, to maintain that force level for the remainder of the trial, although they were free to make as many adjustments as needed. A printed copy of the instructions (adopted from Karwowski (1996), Appendix A) was provided to the participant to read, the instructions were read aloud, and a hard copy remained in front of the participant during all trials. Pacing was achieved using computer-generated tones; one tone was given as a ready signal followed one second later by a different tone signaling the beginning of the exertion. Between exertions, the participant was required to judge the force level and decide to press harder, softer, or about the same for the next exertion. Between the three 25-minute sessions, a minimum of a 5-minute rest period was provided.

All participants returned on the following day for a second session, intended to test intersession repeatability of the MAL data collection and analysis methods. This second session was an exact replication of the first day tasks; participants used the same digit as before with frequencies applied in the same order.

4.6 Analysis

Upon completion, each MAL evaluation trial was analyzed six different ways. The three analysis methods (MSD, LMA, and Filter) were applied to the entire 25-minutes of data, as well as a subset consisting of the first 5 minutes. A software program was written to execute the MSD method, which also included a Butterworth low-pass filter, with a cutoff frequency of 1.5 Hz, for the Filter method. Using the three methods and two data sets resulted in six MAL estimations per frequency, session, and participant. ANOVA was used to test for first and second order effects of digit, analysis method, duration (5 or 25 minutes), frequency, and session with $\alpha = 0.05$. MVEs were analyzed for session and digit effects using ANOVA, again with $\alpha = 0.05$. The resulting ratio between MVE and MAL was then computed for each digit and frequency, and significant effects were compared post-hoc with Tukey HSD tests at $\alpha = 0.05$.

4.7 Results

Digit was the only significant main effect for MVEs exertions, with thumb MVEs significantly higher than index finger ($p < 0.0001$). Neither session, nor the interaction of session and digit showed significance ($p > 0.12$). Values in the second session, however, were about 5% lower on average than those in the first session.

MAL values obtained with the thumb were significantly higher ($p < 0.0001$) than those of the index finger, with means (sd) of 51.2 (27.3) N and 45.1 (15.7) N respectively. Frequency also produced a significant effect ($p < 0.001$), with means (sd) of 54.4 (23.9) N at 3 exertions per minute, 46.9 (21.9) N at 6 exertions per minute, and 43.0 (19.8) N at 9 exertions per minute.

There were no significant differences between the three analysis methods (p = 0.99), and less than 0.5 N between the lowest (MSD, mean = 47.9 N) and highest (LMA, mean = 48.3 N) values. Session was also non-significant (p = 0.08), though session 1 values were on average 3.8% higher than session 2. MAL estimates resulting from analysis of only the first 5 minutes of data were 2.2% higher than the entire 25-minute session, but this difference was not significant (p = 0.34). No significant second-order interactions were found with method (p > 0.4) or duration (p > 0.13).

Significant interactions were frequency X session (p = 0.007), digit X session (p=0.05), and digit X frequency (p=0.004). Frequency X session interaction effects were seen as a small differential effect of session across the three frequencies (Figure 5). For the digit X session interaction (Figure 6), the index finger was significantly higher during session 1 (52.6 and 49.2 N), while the thumb showed no significant difference between sessions (59.2 and 58.3 N). For the digit X frequency interaction (Figure 7), the index finger MALs were significantly less than thumb MALs at both 3 and 6 exertions per minute, while there was no significant difference between digits at 9 per minute.

The ratio of MAL to MVE showed decreasing trends across frequency, with MALs ranging from 25% to almost 60% of MVEs. Although the both MVEs and MALs tended to be higher with for thumb, the MAL/MVE ratio tended to be higher for the index finger (Figure 8).

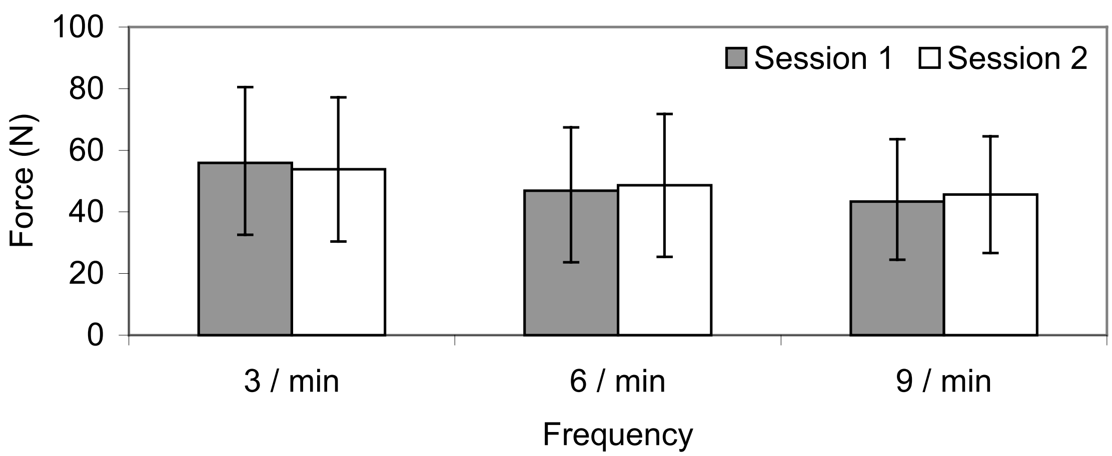

Figure 5. Interaction of exertion frequency and session.

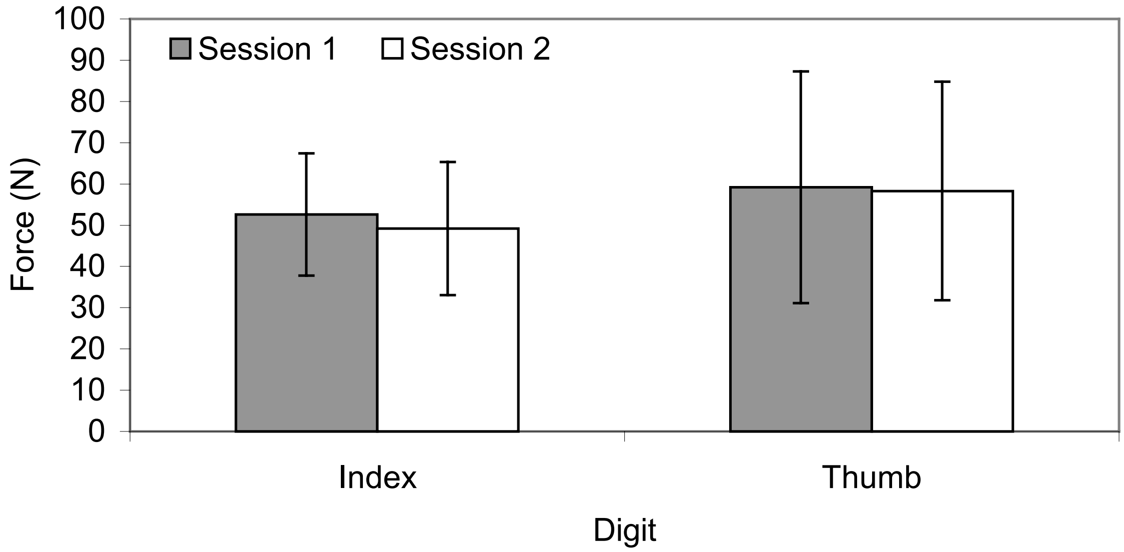

Figure 6. Interaction of digit and session. Significant differences existed with the index finger only. Interaction of exertion frequency and session.

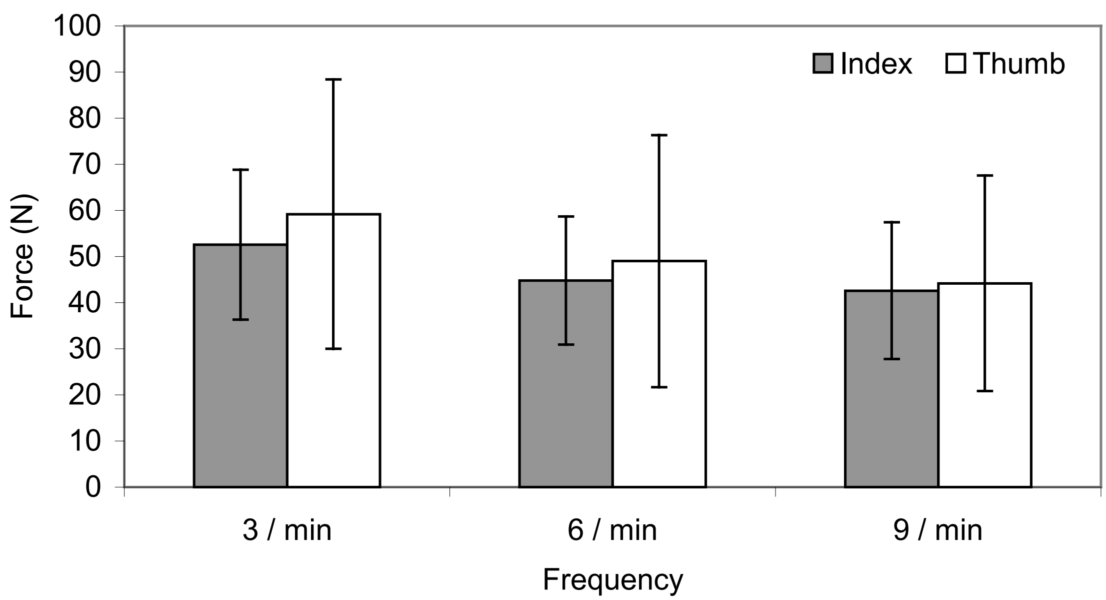

Figure 7. Interaction of digit and frequency. Significant differences were found at 3 and 6/min, but no difference at 9/min.

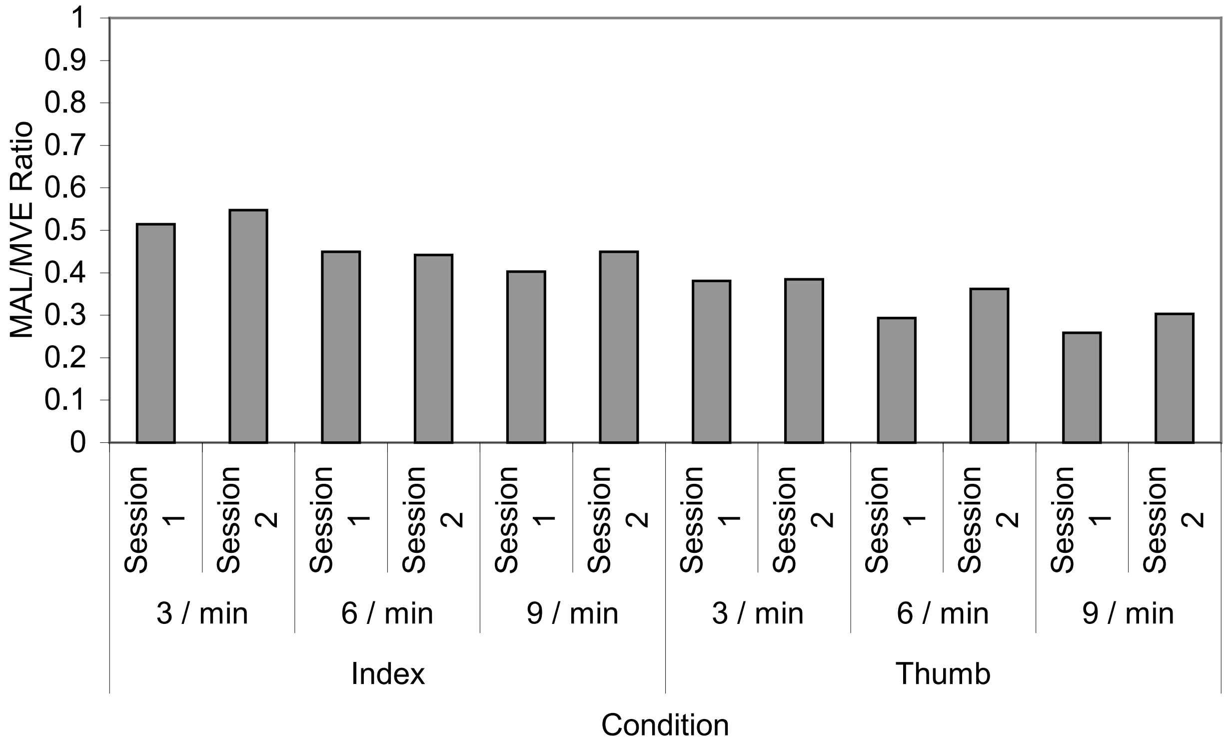

Figure 8. Ratio of MAL to MVE by frequency, digit, and session.

4.7 Discussion

Unlike previous studies, with an external method of regulation, these participants were required to adjust and regulate their force level internally. This adds to the judgments participants must make – not only deciding if they are pressing at an acceptable level, but also maintaining that acceptable force once selected. The goals of this study were threefold: to develop methods to analyze a series of exertion data obtained from a self-regulated MAL evaluation session, to investigate the between session repeatability of this data collection method, and to assess the difference between two different durations of data collection.

The most difficult question to resolve was how to analyze the sequence of discrete exertions to determine the participants' underlying MAL. All three methods selected for analysis were chosen from realistic hypotheses derived from observing the data, leaving open the question: which one is best? The results, however, showed that the methods yielded statistically similar values. Practically, it appears not to matter which method is used for analysis of data obtained from this self-regulation method. Each method, however, may have a role depending on specific needs. When quick results are needed, such as in pilot studies, the LMA method is the fastest and easiest to use, since it only requires calculation of the mean of the last minute of data. The Filter and MSD methods require somewhat more data processing to obtain final MAL estimates. In particular, the MSD method identifies the most stable period, which reduces possible error that may be associated with data at the end of the estimation period, such as may result from fatigue or loss of concentration. The Filter method, on the other hand, removes all the minor adjustments made, resulting in a smoothed adjustment curve. Use of the end-point of the filter may thus be similar to using only the final value obtained from an external adjustment mechanism.

Similar psychophysical studies have used a difference criteria of 15% to verify MAL values between sessions (e.g. Ciriello and Snook, 1983). In this study, inter-session differences were found to be non-significant, with only a 2.5% average difference using the self-adjustment method. This is not only well below 15% but also below the reported just noticeable differences (JND) for finger forces, roughly 6% (Jones, 1998). This suggests that the present self-adjustment method does indeed produce repeatable MAL estimates, since participants likely would not be able to distinguish a difference between their estimates.

Preliminary inspection revealed that force levels appeared to stabilize within the first few minutes, and did not vary substantially in the remaining 15 to 20 minutes of data collection. This observation was confirmed by comparing the first 5 minutes of data to the entire 25-minute test session. Although MALs from 5 minutes tended to be 2.2% higher than from 25 minutes, this difference was both non-significant and below the JND, implying that participants would not have been able to tell the difference between their 5-minute and 25-minute MAL values. Five-minute sessions may therefore be adequate for MAL estimation using the present methodology.

Other effects of note are frequency and digit. There was a decreasing trend in MALs as frequency increased. Specifically, 9 exertions/minute had the lowest MALs, followed by 6/minute, with 3/minute producing the highest MALs. MALs with the thumb were also significantly higher than the index finger. However, the interaction showed that digit was only significant at 3/min and 6/min, while there was no difference between digits at 9 / minute. This suggests that at higher frequencies, the frequency of the exertion has more effect on the MAL than the digit used. These results support previous research on lifting, which showed inverse relationships between maximum acceptable weight of lift (MAWL) and lifting frequency. These previous studies, however, concluded that MAWL data obtained at a rate higher than 6 / min were unreliable (e.g. Ciriello and Snook, 1983; Karwowski and Yates, 1986). A full reliability study, requiring testing of the estimated MAL for a 2-hour period, was not undertaken in this study.

Overall, the results suggest the self-regulating method can produce repeatable estimates of subjective finger force limits, that these limits are insensitive to the analysis method used for estimation of MAL, and that it may be possible to obtain repeatable values from relatively brief experimental sessions. Continued work is needed to further refine and test the present self-adjustment method, the methods of detecting MALs from the resulting sequence of discrete exertions, and the reliability of MAL values obtained.

CHAPTER 5. STRENGTH AND SUBJECTIVE LIMITS FOR A VARIETY OF MANUAL INSERTION TASKS

5.1 Overview

Due to the apparent increase of WRMSDs and increased awareness of ergonomic factors in the workplace, there is an increased need for guidelines for repetitive, hand intensive tasks. One typical type of ergonomic guideline is obtained from strength data for a certain task, as it is important to ensure that workers possess sufficient strength to accomplish a task. As task demands increase, however, a larger percentage of a worker's strength capability is required, and other factors, such as performance and worker comfort, tend to decrease. In the absence of specific strength or biomechanical models, subjective limits are often used, and may be the most appropriate method of establishing such guidelines (Fernandez et al, 1995). It is therefore useful to determine the worker's subjective acceptable exertion level for a given task and set of demands. The primary purpose of this study was to determine the strength capability and acceptable level of exertion with a given set of tasks, designed to closely simulate actual industrial tasks. By simulating actual tasks, results can be directly applied to ergonomic design. This data for this study were collected as part of an investigation to identify insertion force limits for specific tasks at a major automobile manufacturer's assembly line. The data collected were further analyzed to address the aforementioned goals.

5.2 Participants

Fifty current workers from an automobile assembly line were recruited for participation in the study. The automobile facility provided both the participants and testing facilities. Participants were randomly selected by facility staff from among line workers, and were tested during their normal work shift. To ensure a healthy test population, workers were selected from those free of OSHA recordable injuries for at least one year and asked if they would like to participate. The selection of workers may introduce a possible bias from facility staff; however, the staff was reminded that a truly random sample would produce more reliable results, and that it was in their best interest to avoid bias in selection. On the respective day of testing, two-thirds of the participants had worked one-hour or less prior to the experimental session, while the remaining one-third had been on the assembly line for five hours prior to testing. No additional compensation was provided for participation in the study. Seven participants declined to participate, but alternates were available for four of their scheduled time slots. Four participants did not arrive for their scheduled testing session, reducing the total participant count to 43. One participant withdrew before completion due to late arrival and completed nine of the ten tasks.

Upon arrival at the testing location, participants completed an Informed Consent procedure approved by the university IRB, including signing an informed consent form (IRB #00-217). Participants then provided background information including age, service time, and recent history of pain or injury. The facility had previously determined that all participants were free of OSHA recordable injuries for at least six months.

Of the 43 participants who were tested, 28 (65%) were males and 15 (35%) were females. The right hand was dominant for 37 (86%) of the participants, who varied in age from 26 to 63 years of age with □mean (sd) of 38.5 (7.7) years. The mean (sd) length of employment reported by participants was 8.7 (4.1) years. Over half of the participants had 10 or more years of experience at the plant. Anthropometric data was obtained as in the prior study (see Chapter 4, page 20), with the exception of shoes. Since work on the line requires steel-toed boots, participants were not asked to remove boots for measurements. Heights and weights reported therefore include steel-toed boots (Table 4).

Table 4. Anthropometric data from industrial population (n = 43).

	Mean	Std Dev
Stature (cm)	174.0	8.9
Body Mass (kg)	81.3	16.7
Standing Shoulder Height (cm)	146.3	7.8
Upper Arm Length (cm)	29.1	2.5
Lower Arm Length (cm)	25.5	1.7

5.3 Equipment

A fixture (Figure 9) was constructed to simulate 10 selected assembly tasks (see Table 5 below). Figure 10 demonstrates samples of each selected coupling. Force data were collected with a three-axis load cell (AMTI model MSA-6-500) and sampled at 60 Hz with LabVIEW^{tm}

software. The force transducer was mounted using bolts such that it could quickly be re-positioned on the fixture for the next task.

Figure 9. Data Collection Fixture

Figure 10. Couplings used (left to right: thumb push, lateral pinch push, index push)

5.4 Design

Tasks selected for simulation were based on observations made at two neighboring U.S. sites of an automobile manufacturer. Facility personnel selected 11 assembly line workstations that had been identified by the safety staff as in need of further ergonomic study. These workstations were observed on a site visit, and a videotape was made for further task analysis in the laboratory.

To reduce the number of tasks studied to a reasonable number, it was proposed that the most common hand couplings and body postures be used to develop guidelines that could in turn be used for similar tasks. Three hand couplings were identified for further study: index push, thumb push, and lateral pinch-push. In the latter coupling, the thumb and index finger pinch an object and a push force is applied perpendicular to the direction of pinch. Four body postures were also identified:

1) Upright overhead reach, defined as hand force applied at eye-level or above
2) Upright elbows abducted with hand force located between the waist and eye-level
3) Standing, waist bend with a forward reach
4) Seated with a forward reach.

Each of the 12 combinations (3 couplings x 4 postures) was associated with at least one observed assembly line workstation. Facility personnel then reduced the number to 10 for further study (Table 5), with force direction matching the associated line process. Actual assembly line processes and their equivalent tasks as simulated in the laboratory are shown in Appendix B. The set of 10 tasks did not represent a full factorial design, nor was it possible to fully balance presentation order with a reasonable number of participants. It was therefore decided to randomize task presentation order. For each participant, the initial task, either task 1 or task 4 that was randomly assigned, was repeated later in the session to assess repeatability within this study.

Table 5. Posture-coupling combinations selected for study

Posture	Coupling		
Upright, Overhead Reach	1 Index push	2 Thumb push	3 Lateral pinch push
Upright, Elbows Abducted	4 Index push	5 Thumb push	6 Lateral pinch push
Waist Bend, Forward Reach	7 Index push	8 Thumb push	
Seated, Forward Reach	9 Index push	10 Thumb push	

Videotape analysis of several assembly tasks showed that workers commonly inserted 4 to 6 items per automobile, with a cycle time of approximately 52 seconds. The upper level is approximately 6 insertions per minute, and was the rate selected for use in determining subjective force limits.

5.5 Procedure

The procedure for this study was similar to that of the first study on MAL evaluations methods (see Chapter 4). Based on previous results indicating that five minutes of adjustment did not produce statistically different results than the typical 25-minute adjustment period (see Chapter 4), a five-minute adjustment period was justifiable to obtain MALs for each selected task. For each given task, the participant performed three to four MVEs and then continued with a five-minute computer-paced MAL evaluation period. It was assumed they were familiar with the context of the experiment, as participants were recruited from those actually doing these tasks. Therefore, there was no video shown for familiarization. Upon completion of the five-minute MAL evaluation, the force transducer was repositioned, to the next predetermined, randomized task allowing at least 90 seconds of rest, and the MVE and MAL evaluation was repeated.

MAL estimation sessions were analyzed with the minimum standard deviation (MSD, Chapter 4) method. This method appeared more rigorous than the last minute average (LMA) method, and appeared better than the Filter method when used on shorter sessions. The primary analysis methods for the data consisted of determining means and standard deviations for both the MVEs and MALs for each task, along with assessing any relationship between the two measures. One-way analysis of variance (ANOVA) was performed followed post-hoc by Tukey Honestly Significant Difference (HSD) tests for effects of task on both MVE and MAL with $\alpha = 0.05$. Correspondence between MVE and MAL were assessed by determining the ratio between the two and using linear regression. Individual factors, including all anthropometric measures collected, age, gender, and years of experience on the assembly line were tested for correlation to both MVE and MAL values using linear regression. Stepwise forward multiple regressions were used to test for the combined effect of the factors on each task. Intra-session repeatability of the duplicated tasks was assessed using linear regression.

5.6 Results

Mean MVE and MAL force values for both males and females in each of the 10 tasks are shown in Table 6. Additionally, the ratio between MAL and MVE is reported, and the R^2 values obtained via linear regression. The MAL/MVE ratio varied from 0.52 to 0.63, with most ratios between 0.55 and 0.60. All R^2 values were on the order of 0.5. When the genders were combined, observed MALs ranged from 54% to 62% of MVE, averaging 58% (Figure 11).

Table 6. Mean force values (N), MAL/MVE Ratio (%), and R^2 for participants (n = 40)

			MVE		MAL		MAL/MVE Ratio		
		Task	Male	Female	Male	Female	Male	Female	R^2
Overhead	Index	1	120.9	76.6	66.7	41.5	55.2	54.2	0.59
	Thumb	2	147.8	83.8	91.5	51.0	61.9	60.9	0.55
	L.P.	3	145.9	111.4	90.7	69.7	62.2	62.6	0.45
Elbows Abducted	Index	4	108.8	77.7	59.0	42.3	54.2	54.4	0.42
	Thumb	5	186.3	109.8	101.5	61.5	54.5	56.0	0.55
	L.P.	6	160.5	98.3	91.2	51.2	56.8	52.1	0.56
Waist Bend	Index	7	95.0	64.3	54.6	38.6	57.5	60.0	0.57
	Thumb	8	123.0	78.6	71.9	46.4	58.5	59.0	0.63
Seated Reach	Index	9	126.3	95.9	75.9	60.8	60.1	63.4	0.50
	Thumb	10	198.0	143.2	113.5	80.2	57.3	56.0	0.41
		Mean	141.3	94.0	81.7	54.3	57.8	57.8	0.52

L.P. = Lateral Pinch-Push

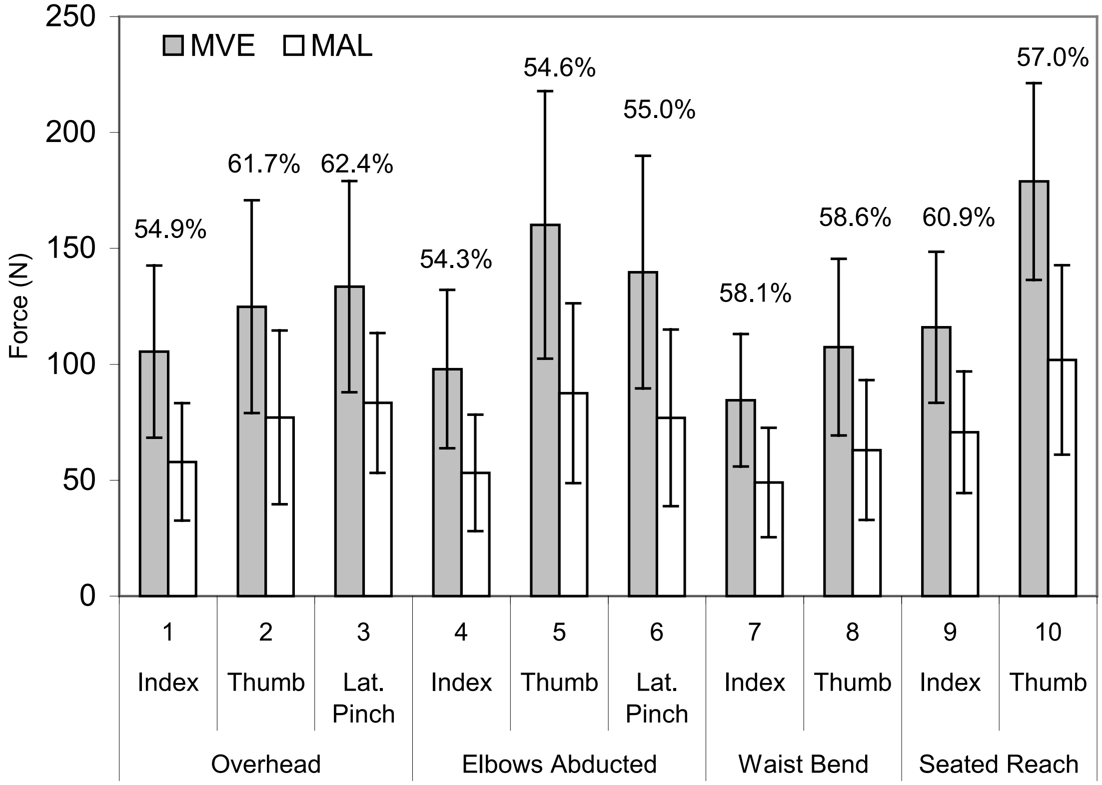

Figure 11. Task means for MVE and MAL. Numbers indicate the associated MAL/MVE ratio.

A one-way ANOVA found task to be a significant factor for both MVE and MAL ($p < 0.0001$). Results from the subsequent Tukey HSD tests are shown in Table 7 and Table 8 respectively. For both MVE and MAL, ordering of the last five and the first two tasks was the same. In general, the index finger tasks were lower than both the thumb and lateral pinch-push tasks. The only exception was task 8, which was a thumb push in the waist bent posture. The waist bent and seated reach posture produced the lowest and highest values of all index and thumb tasks respectively.

Table 7. Tukey HSD groupings for MVEs

Task	7	4	1	8	9	2	3	6	5	10
Mean	84.5	97.9	105.4	107.4	115.9	124.8	133.5	139.7	160.2	178.9
Grouping	1	1	1	1						
	2	2	2	2	2	2				
	3	3	3	3	3	3	3			
		4	4	4	4	4	4	4		
			5	5	5	5	5	5	5	
					6	6	6	6	6	
							7	7	7	7
									8	8

Table 8. Tukey HSD groupings for MALs

Task	7	4	1	8	9	6	2	3	5	10
Mean	49.0	53.2	57.9	63.0	70.6	76.9	77.1	83.4	87.5	101.9
Grouping	1	1	1	1	1					
	2	2	2	2	2	2	2			
	3	3	3	3	3	3	3	3		
	4	4	4	4	4	4	4	4	4	
			5	5	5	5	5	5	5	
				6	6	6	6	6	6	6
					7	7	7	7	7	7
								8	8	8

A matrix of all R^2 values from the regression analysis for the individual difference factors (age, gender, anthropometrics, and years of experience) appears in Appendix C. R^2 values for MVE ranged from 0.0 (age: task 1 and 9; years of experience: task 4) to 0.458 (gender: task 2). Factors that showed moderate ($R^2 > 0.25$) correspondence with MVE are: gender: tasks 1, 2, 5, 6, 7, 8, and 10; stature: task 6 and 10; body mass: task 2 and 5; upper arm length: task 2; lower arm length: task 2, 6, 8, and 10; and standing shoulder height: task 2, 5, 6, and 10. For MALs, R^2 varied from 0.0 to 0.275. The only tasks with any single factor R^2 approximately 0.25 or above were tasks 2 and 6, with R^2 of 0.275 and 0.248 respectively with gender. Combining the various factors in stepwise regression resulted in R^2 higher values than the individual factors. Table 9 and Table 10 summarize the factors that were obtained from the stepwise regression procedures for MVE and MAL respectively. For MVEs (Table 9), it can be seen that for about half the tasks, a combination of several factors may result in an acceptable regression model ($R^2 > 0.4$).

The case is not the same for MALs (Table 10), where stepwise regression revealed little about the behavior of these force measures, as in many cases, the results of multiple regression were no different than linear regression using gender as a factor. This suggests that while strength capabilities may have some relation to anthropometry, subjective limits are not as strongly related to simple body dimensions.

Table 9. Stepwise regression results for MVE by Task

	MVE	
Task	Factors	R^2
1	Gender, Stature, Standing Shoulder Height, Hours of work prior to testing	0.429
2	Gender, Body Mass, Upper arm length	0.529
3	Body mass, Stature, Lower arm length, Years of experience	0.370
4	Gender, Age	0.274
5	Body mass, Upper arm length, Lower arm length, Standing shoulder height, Hours of work prior to testing	0.606
6	Gender, Age, Hours of work prior to testing	0.534
7	Gender, Hours of work prior to testing	0.319
8	Gender, Hours of work prior to testing	0.413
9	Gender, Hours of work prior to testing	0.245
10	Gender, Hours of work prior to testing, Years of experience	0.456

Table 10. Stepwise regression results for MAL by Task

Task	Factors	R^2
1	Gender, Standing shoulder height, Lower arm length	0.312
2	Gender, age	0.316
3	Gender	0.112
4	Gender	0.103
5	Gender, Hours of work prior to test	0.281
6	Gender, Age, Years of experience	0.368
7	Gender	0.107
8	Gender, Lower arm length, Years of experience, Hours of work prior to testing	0.269
9	Gender	0.078
10	Gender, Years of experience	0.196

Linear regression results from the repeated trials show intrasession correspondence between the first and second trial to be relatively high for both MVE and MAL, with R^2 of 0.65 and 0.70 respectively. When a regression line was forced to have a zero intercept, the resulting slopes were 1.03 and 1.01 respectively, indicating the trials were closely related (see Figure 12 and Figure 13).

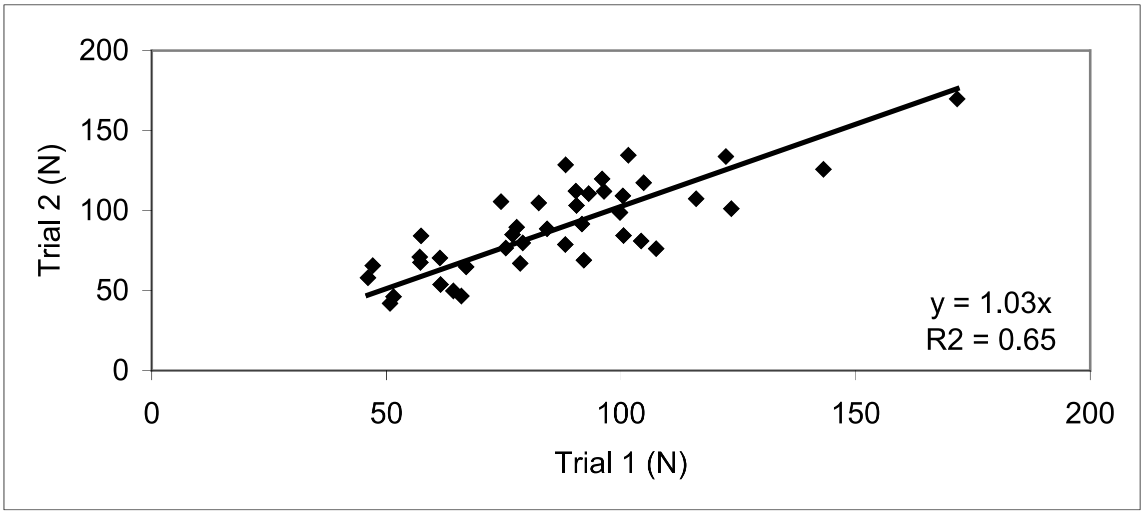

Figure 12. Linear regression of MVE trial 1 vs. trial 2.

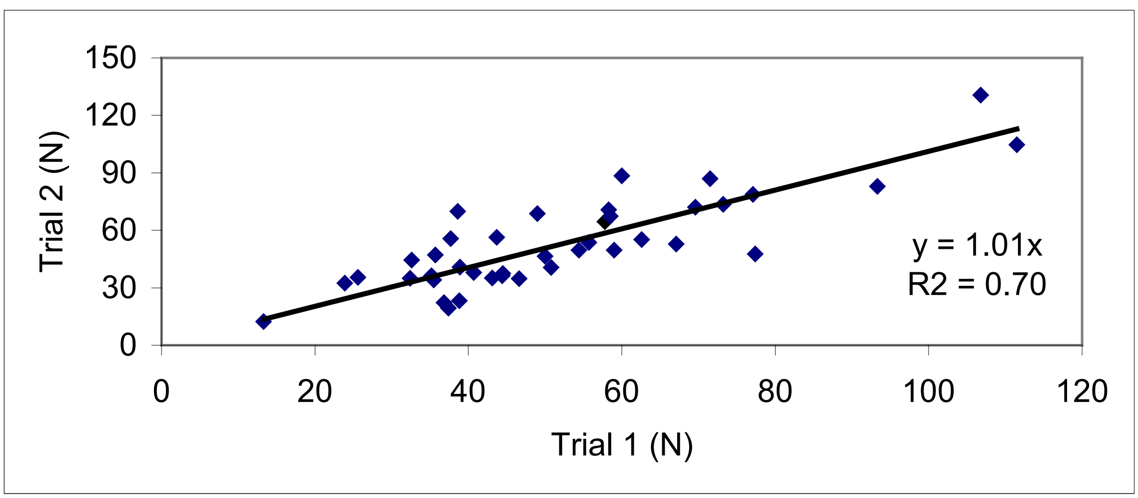

Figure 13. Linear regression of MAL trial 1 vs. trial 2.

5.7 Discussion

The primary aim of this study was to determine how several occupational factors, such as posture and insertion digit, affected strength capability and acceptable limits as determined from an industrial population. In general, it was found that the thumb was both stronger and had higher subjective limits than the index finger in the same posture. The lowest values were found in the waist bend posture (Tasks 7 and 8), as expected due to extended reach required, while the seated posture (Tasks 9 and 10) had the highest values, perhaps due to an ability to lean without loss of balance. MALs were observed to be between 54 and 62% of MVE, averaging 58%. This number is higher than was expected from the previous study (Chapter 4, roughly 40%). One possible explanation for the difference is that the present participants were more familiar with the tasks and the context of the experiment. All had more than one year of experience on the assembly line from which these tasks were taken, and they had first-hand knowledge of the demands of a two-hour job rotation. Additionally, they may have been accustomed to physical exertions of this sort, and therefore willing to give higher values.

Most tasks selected for the current study can be roughly equated to previously studied tasks (Table 11). Tasks 3 and 6, both lateral pinch-push, have not been studied previously. They could be compared to a grip push, for which the Army has established guidelines, however it is likely the grip push has higher strength capabilities due to more digits being involved. Tasks 2, 5, 8 and 10 are all thumb pushes, which can be roughly equated with studies by Hertzberg (1973) and Schoorlemmer and Kanis (1992) that included data on the thumb push. The current study, however, required an outstretched arm for most participants, while the previous studies typically set the elbow at 90^{o} flexion. Tasks 1, 4, 7, and 9 are index pushes, which are comparable to data from Astin (1999), Dickson (1972) and Hertzberg (1973). Again, the current study allowed outstretched arms and allowed participants to adjust posture to reach a maximum effort, while previous studies have used specified postures. By constraining the participant to a set posture, the force can be limited to what the surrounding muscles can produce. Given the postures currently being studied, the outstretched arm allows participants to lean into the digit, and would likely increase force values from those obtained when only muscles in the hands and arms are used. While this procedure does not match closely with previous studies, it is a more accurate representation of what is observed on assembly lines.

Table 11. Previous studies roughly equated to current tasks.

Coupling	Experimental Task	Previous Studies/Guidelines
Thumb Push	2, 5, 8, 10	Schoorlemmer and Kanis (1992) Hertzberg (1973)
Index Push	1, 4, 7, 9	Hertzberg (1973) Dickson (1972) Astin (1999)
Lateral Pinch Push	3, 6	
Grip Push		Army (MIL-STD-1472D)

When compared to previous studies, it is notable that MVE values were as much as 300% higher than reported in previous studies (Table 12). The reasons behind this difference are not clear, but may be a result of several factors. Previous studies placed the participant in a fixed posture to isolate the exertions being examined. The current research attempted to better match actual industrial tasks, and therefore allowed participants to adjust their posture in order to obtain a maximum effort. Additionally, since many of the postures were standing or reaching, participants were able to lean and apply body weight on the digit being tested. However, this still differs from a whole body exertion since the primary muscles and joints affected are in the upper extremity. Another explanation for such higher values may be the population used. A trained industrial population may provide higher values than the population as a whole due to experience or perceived expectations. Since the present goal was to investigate strength capabilities in actual industrial tasks, not constrained laboratory postures, the differences seen were expected and highlight potential limitations incurred with using inexperienced laboratory volunteers.

Table 12. Mean MVEs compared to previous studies (all data in Newtons)

Posture	Coupling	Task #	Current Data Male	Current Data Female	Schoorlemmer and Kanis (1992) Male	Schoorlemmer and Kanis (1992) Female	Astin (1999) Male	Astin (1999) Female	Hertzburg (1973) Male	Dickson (1972) Male
Overhead	Index	1	120.9	76.6			52.6	39.3	56.8	45.1
	Thumb	2	147.8	83.8	86.9	68.5			77.4	
	L.P.	3	145.9	111.4						
Elbows Abducted	Index	4	108.8	77.7			52.6	39.3	56.8	45.1
	Thumb	5	186.3	109.8	86.9	68.5			77.4	
	L.P.	6	160.5	98.3						
Waist Bent	Index	7	95.0	64.3			52.6	39.3	56.8	45.1
	Thumb	8	123.0	78.6	86.9	68.5			77.4	
Seated	Index	9	126.3	95.9			52.6	39.3	56.8	45.1
	Thumb	10	198.0	143.2	86.9	68.5			77.4	

L.P. = Lateral Pinch Push

Direct comparisons between the MAL values obtained with the current research and previous research are hard to obtain. Except for Schoorlemmer and Kanis (1992), who reported and average comfortable/maximum force ratio, these previous studies have not attempted to obtain acceptable exertion levels for these types of tasks. Table 13 displays the 5th and 10th percentile MAL obtained from mean and standard deviation data in the current study as compared to several methods of determining guidelines applied to previous studies. The two methods used are the Kodak (1986) method, which is to take 20% of the weaker worker's strength capacity, and the ACGIH (2000) method, which is to determine a maximum normalized peak force (see also section 2.4). The lower MAL percentiles obtained from the current study roughly compare to the ACGIH Action Limit applied to previous studies.

Table 13. Current MALs compared to other methods of determining acceptable forces (all values in Newtons)

		Task									
		Overhead			Elbows Abducted			Waist Bent		Seated	
		Index	Thumb	L.P.	Index	Thumb	L.P.	Index	Thumb	Index	Thumb
		1	2	3	4	5	6	7	8	9	10
Current Study	5th percentile MAL	26.0	29.0	41.6	22.5	35.6	30.5	21.1	25.2	35.8	48.2
	10th percentile MAL	30.5	35.0	47.8	26.6	42.4	36.5	24.9	30.1	41	55.9
	ACGIH[2] Guideline	34.5	37.7	50.1	35	49.4	44.2	28.9	35.4	43.2	64.4
Schoorlemmer and Kanis (1992)	Kodak[1]		6.3			6.3			6.3		6.3
	ACGIH[2]		39.1			39.1			39.1		39.1
Astin (1999)	Kodak[1]	5.9			5.9			5.9		5.9	
	ACGIH[2]	23.7			23.7			23.7		23.7	
Hertzburg (1973)	Kodak[1]	8.1	11.2		8.1	11.2		8.1	11.2	8.1	11.2
	ACGIH[2]	25.6	34.8		25.6	34.8		25.6	34.8	25.6	34.8
Dickson (1972)	Kodak[1]	9			9			9		9	
	ACGIH[2]	20.3			20.3			20.3		20.3	

[1] 20% of the observed 10th percentile strength capacity
[2] Normalized peak force below the ACGIH Action Limit for the observed strength data

These comparisons suggest that previous assumptions, such as the Kodak guidelines, on the acceptability of tasks may not be appropriate for all industrial tasks. Guidelines based on laboratory studies not designed to replicate actual task may have little bearing on actual industrial tasks, due to the stringent posture controls and lack of similarity to real tasks. The ACGIH TLV guidelines for hand intensive activities, however, were within two to five Newtons of the present 10th percentile MAL data, suggesting that this TLV can be used to successfully design tasks acceptable to up to 90% of workers. Previous studies have recommended designing for 85% acceptability (e.g. Waters, et al., 1993; Potvin, et al., 2000), however, these data suggest that the use of the ACGIH TLV may increase acceptability to 90%.

CHAPTER 6. INVESTIGATION OF HAND USE EFFECTS ON MAL AND MVE

6.1 Overview

Previous studies have found differences of approximately 5% between right and left hand, with the higher values in the right hand (Mathiowetz, 1985; Konz, 1995). Since up to 90% of the population is right-handed, designing with these values is usually acceptable. Many industrial tasks, however, may require the use of a certain hand for force application due to the location or direction of the force required, which may therefore require the use of the non-dominant hand. For this reason, it is important to assess any potential differences between strength capabilities or acceptable limits associated with the hand used.

In Chapter 5, several factors, gender, posture, coupling, and force direction, were evaluated for their effects on both strength capabilities and subjective limits. One potentially important factor that was excluded from the study was the possible effect due to the hand used for the task. A third study was thus conducted to quantify the effects of hand used on force capability and acceptable limits in manual insertion tasks.

6.2 Design

Testing all 10 tasks (Chapter 5) with both hands would result in 20 tasks and over 4 hours of testing. To reduce experimental time, a subset of five of the original 10 posture-coupling combinations used in the industrial data collection was used. It was desired that each participant experience each posture and each coupling at least once. Refer to Table 5 (p. 32) for the original set of tasks. These original tasks were divided into two subsets (A and B) of five tasks each shown in Table 14. Each participant experienced one of the two subsets.

Table 14. Subsets (A and B) for hand dominance testing

Posture	Coupling		
Upright, Overhead Reach	Index push A	Thumb push B	Lateral pinch push A
Upright, Elbows Abducted	Index push B	Thumb push A	Lateral pinch push B
Waist Bend, Forward Reach	Index push A	Thumb push B	
Seated, Forward Reach	Index push A	Thumb push B	

Presentation order was randomized as before, with each participant experiencing each posture-coupling combination twice. To reduce possible conscious or unconscious force matching between hands, participants experienced all five positions once, then the order was repeated using the other hand. Half of the participants started with their right hand, the other half began with their left. This order was assigned without regard to the participant's dominant hand, which was self-declared by the participant. The entire design is summarized in Table 15.

Table 15. Experimental Design for Hand Dominance Testing

Subject	Gender	Subset	Hand Order	Subject	Gender	Subset	Hand Order
1	M	A	R – L	11	M	A	L - R
2	M	B	R – L	12	M	B	L - R
3	M	A	R – L	13	M	A	L - R
4	M	B	R – L	14	M	B	L - R
5	M	A	R – L	15	M	A	L - R
6	F	B	L - R	16	F	B	R – L
7	F	A	L - R	17	F	A	R – L
8	F	B	L - R	18	F	B	R – L
9	F	A	L - R	19	F	A	R – L
10	F	B	L - R	20	F	B	R – L

6.3 Participants

Sample size was set at 20 participants, as similar studies on grip and pinch strength have found significant differences between hand forces with 18 to 24 participants (McMullin and Hallbeck, 1991; O'Driscoll, et al., 1992; Hallbeck and McMullin, 1992; Ramakrishna, et al, 1994). Participants were recruited from the student population at Virginia Tech. Each participant completed an informed consent procedure approved by the Institutional Review Board of Virginia Tech (IRB #00-217) and was compensated at a nominal rate for their time. Age ranged from 19 to 38 with mean (sd) of 24.6 (4.9) years. Although not part of the design, balancing of hand dominance was attempted. However, due to the relatively low population of left-handed people, there were eight left- and 12 right-handed participants. Four participants had previous manufacturing experience, ranging from 1 to 3 years. Anthropometric data was collected as in the previous investigations. Participants had mean (sd) stature and body mass of 170.2 (6.9) cm and 76.3 (18.1) kg respectively. Standing shoulder height, upper and lower arm length means (sd) were 141.9 (6.2), 29.0 (2.1), and 25.4 (1.3) cm respectively.

6.4 Equipment

The fixture shown in Figure 9 (p. 18) was also used for this study. Force data were again collected with a three-axis load cell (AMTI model MSA-6-500) and sampled at 60 Hz with LabVIEW^{tm} software. The force transducer was mounted such that it could quickly be re-positioned on the fixture for the next posture-coupling combination.

6.5 Procedure

As in the two prior studies, participants were instructed to press normal to the transducer, and data was monitored to ensure participants followed instructions. The same data collection procedure as in Chapter 5 was used, with each participant doing three to four MVE trials followed by one five-minute MAL trial.

The data were analyzed several ways. Simple means were found for MVEs and MALs and the ratio between the two was determined. Regression was used to determine the correlation between these two measures. Previous studies (e.g. Mathiowetz et al., 1985) have examined the difference between left and right hand strength, but generally have not obtained enough left-handed participants to differentiate between the right hand and the dominant hand. With almost 50% of present participant self-declaring themselves as left-handed, it was possible to test for both left vs. right hand and dominant vs. non-dominant hand without equating right with dominant. Therefore, two hand effects were considered: hand dominance (dominant, non-dominant) and hand used (right, left). First and second order effects of task and hand dominance were tested using ANOVA, which was also used to determine effects of task and hand used ($\alpha = 0.05$).

6.6 Results

For MVEs, both hand used and dominant hand were significant. Force values for the left hand were 5% lower than the right hand, with mean (sd) of 83.30 (31.06) and 87.29 (31.58) N respectively. The dominant hand produced MVEs 6% higher than the non-dominant hand, with means (sd) of 87.82 (32.41) and 82.76 (30.12) N respectively. Both of these differences were significant ($p = 0.006$ for both). Task and gender were significant in both cases ($p < 0.0001$). Task means varied from a low of 57.95 (20.24) N in task 7 to 119.31 (25.45) N in task 10. Force values for males were 25% higher than female. There were no significant interactions between hand factors and task ($p > 0.08$).

For the MALs, hand used was significant ($p = 0.04$) with the right hand producing values 6.5% higher than the left and mean (sd) of 46.13 (20.25) and 43.16 (19.24) respectively. Hand dominance, however, was not significant ($p = 0.15$), although there was a 4% difference in means. Task and gender was significant for both ($p < 0.0001$). There were no significant interactions between hand factors and task ($p > 0.8$).

Mean MVE and MAL force values for the left and right hands are shown in Table 16 and Table 17 respectively. The correspondence of MAL and MVE is represented by R^2 in the tables.

Table 16. Means force values, MAL/MVE ratios, and R^2 for student population (left hand)

	MVE		MAL		MAL/MVE Ratio (%)		
Task	Male	Female	Male	Female	Male	Female	R^2
1	79.5	52.7	41.2	23.9	51.8	45.4	0.41
2	94.1	72.2	53.8	34.2	57.2	47.4	0.51
3	103.8	63.4	53.4	42.4	51.4	66.9	0.40
4	70.5	59.6	39.6	23.0	56.2	38.6	0.39
5	138.4	88.4	53.6	46.8	38.7	52.9	0.13
6	105.1	85.1	51.0	43.8	48.5	51.5	0.57
7	62.7	43.9	31.9	25.0	50.9	56.9	0.47
8	78.6	60.7	47.5	28.6	60.4	47.1	0.70
9	89.9	62.8	44.9	40.0	49.9	63.7	0.23
10	123.8	114.4	75.7	68.0	61.1	59.4	0.07
Mean	94.6	70.3	49.3	37.6	52.6	53.0	0.39

Table 17. Means force values, MAL/MVE ratios, and R^2 for student population (right hand)

	MVE		MAL		MAL/MVE Ratio (%)		
Task	Male	Female	Male	Female	Male	Female	R^2
1	77.1	58.9	40.4	30.9	52.4	52.5	0.63
2	105.7	71.6	58.9	37.2	55.7	52.0	0.37
3	108.5	77.4	58.8	53.0	54.2	68.5	0.40
4	78.8	60.5	34.4	23.8	43.7	51.1	0.25
5	132.9	100.6	59.6	63.2	44.8	37.0	0.29
6	102.9	90.3	54.6	50.7	53.1	58.7	0.47
7	68.3	49.3	35.6	28.3	52.1	48.3	0.51
8	96.9	60.1	52.6	26.1	54.3	105.2	0.59
9	89.1	72.6	44.9	47.3	50.4	69.8	0.07
10	145.7	103.7	74.8	59.9	51.3	27.3	0.32
Mean	100.6	74.5	51.5	42.0	51.2	57.0	0.39

6.7 Discussion

Several earlier studies (e.g. Kellor, et al., 1971; Mathiowetz, et al., 1985) have investigated the difference between the strength of the hand in various postures. These studies tended to have a relatively low number of left-handed participants. Instead of assessing dominant vs. non-dominant strength, they grouped right and left-handed participants together and only reported the difference between the right and left hand. Mathiowetz, et al. (1995) reported a difference of 2% to 6% on various grip and pinch tasks, with the right hand producing the higher values in all cases. This is consistent with the 5% difference seen across MVE tasks in the current study, with the right hand, again, producing higher values. In the present study, however, an specific effort was made to recruit left-handed participants resulting in a 60/40 ratio of right to left-handed participants. Of particular note is the actual value obtained with the dominant hand vs. the right hand. Forty percent of participants were left-handed; however, the mean force produced by the right hand (across all participants) was 87.3 N while it was 87.8 N for the dominant hand. That is, the right hand was generally stronger than the left, for all participants regardless of dominance. For this reason, more credence is lent to the hypothesis that the right hand is generally stronger than the left hand.

Konz (1995) summarizes several studies investigating the difference between dominant and non-dominant hand use on hand strength. A 6% difference was reported in grip strength, with finger strength tending to average a 5% difference, non-dominant being lower in all cases. A difference of 6% was observed in the strength capability portion of the present study, which is consistent with these previous studies.

There is a lack of published literature assessing potential difference between the hand factors and acceptable limits. In this study, a significant difference was only observed with right vs. left hand (6.5%). Non-dominant MALs were approximately 96% of dominant values, and while this difference may not be statistically significant, it could still be considered in task design. However, the results from this study have been consistent with previous studies of hand strength, and suggest that the consideration of the hand to be used for an insertion task may not be extremely important in design.

CHAPTER 7. THE USE OF A STRENGTH PREDICTION MODEL IN PREDICTING MANUAL INSERTION FORCES

7.1 Goals

Biomechanical strength prediction models can be used to assess loads placed on the human performing various tasks. One of the more popular models, the Three-Dimensional Static Strength Prediction Program (3DSSPP), was developed by The University of Michigan and is often used for heavy material handling tasks, such as lifting or pushing. The validity of this model was tested by the developers and found to perform “reasonably” when predicting population strength from posture data (Chaffin and Erig, 1991). Others have also used this model to predict low-back stress for research purposes (e.g. Mirka, et al, 2000; Lavender, et al, 2000). It is unclear, however, if the model can accurately predict population strengths for more localized forces versus whole body tasks. The goal of this study was therefore to assess if the model would be able to predict mean population strength for the ten tasks examined in the Chapter 5.

7.2 Input to 3DSSPP

For each of the 10 postures used in the previous studies, measurements were taken from the fixture (Figure 9, pp 18) to determine the location of the hand when applying force. These hand locations were input into 3DSSPP and body posture was manually adjusted to reflect observations made during testing. Figure 14 demonstrates the evolution of one task, from the observed assembly line task, to the experimental simulations, to the posture data input into 3DSSPP. There were several limitations encountered when working with 3DSSPP. In particular, it was difficult to simulate a seated position, as 3DSSPP assumes the human is always standing and keeps the feet flat on the floor. In cases where software limitations such as this occurred, lower body analyses were ignored, instead focusing on predictions generated only for the upper body.

Six anthropometric percentiles (5^{th}, 50^{th}, 95^{th}, male and female) were tested for each of the ten tasks. Hand location was kept constant throughout the six anthropometric percentiles with slight modifications made in posture as anthropometry changed.

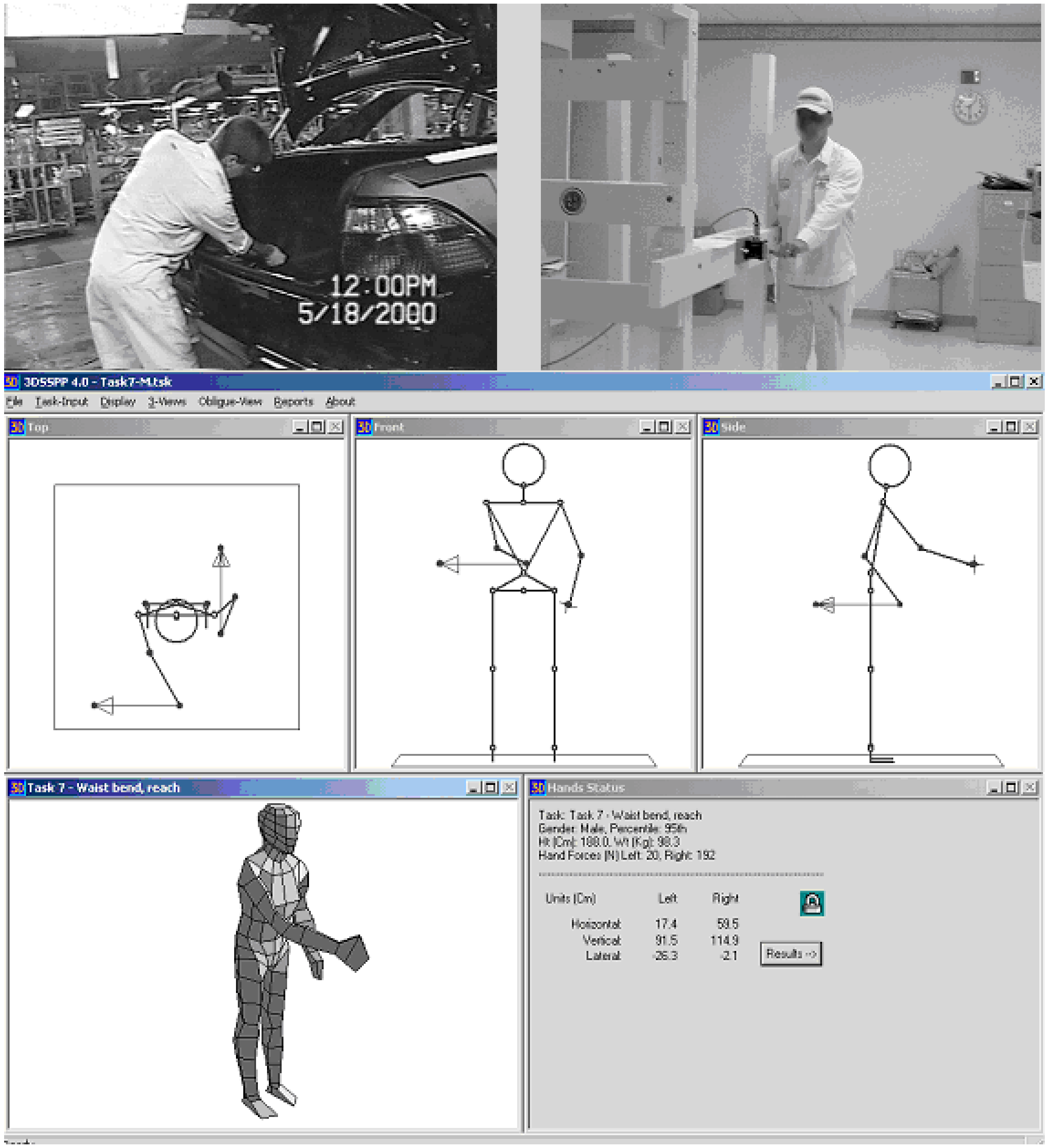

Figure 14. Observed task (top left), experimental simulations (top right), and 3DSSPP model (bottom) for tasks 7 and 8

7.3 Criteria used for force selection and comparison

Chaffin and Erig (1991) describe a study similar to this, in which verification of the 3DSSPP model was assessed in whole body tasks. In their study, hand loads were increased until a single joint or muscle group reported a 50th percentile capability. They concluded that for an unbiased model, this would be the predicted mean for the given population. A similar method was used in the present study. Once the desired posture was input, hand force was then increased until the program reported that a single muscle group or joint moment had reached the 50^{th} percentile. Force was iterated by 0.1 Newton, and the largest value that resulted in a 50^{th} percentile was recorded as the predicted population mean.

Means from the 40 participants in the MVE portion of the industrial data collection (Chapter 5) were then compared to the 3DSSPP predicted means. Stature percentile was determined for each participant using United States Air Force stature data (Webb Associates, 1978), as these are the same anthropometric data used in 3DSSPP. Participants were then blocked into one of six stature groups: 1^{st} to 25^{th}, 26^{th} to 75^{th}, and 76^{th} to 99^{th} for both males and females. Mean heights from the participant blocks closely matched the corresponding percentile for height ($R^2 = 0.94$), suggesting this was an acceptable method of grouping participants. Population means from each group were then obtained and compared using linear regression to the predicted population means reported by 3DSSPP for the 5^{th}, 50^{th}, and 95^{th} percentile males and females.

7.4 Results

The predicted mean MVE was plotted against the observed mean MVE for all tasks and percentile groups and a regression line was fit to the scatter plot (Figure 15). The regression line had a slope of 1.19 and an R^2 of 0.40. The slope of the line is close to 1, with a intercept of –2.8N, indicating the model has a tendency to slightly underestimate the population mean over the variety of tasks studied. When analyzed by task, R^2 varied from a low of 0.17 for task 3 to 0.94 for task 10 (Table 18). The slope of the resulting regression line for each task ranged from 0.15 to 0.88, with nine of the ten slopes less than 0.6, indicating a relatively poor fit for the majority of the tasks. For 50% of the tasks, 3DSSPP identified the elbow as the limiting joint, while the shoulder was limiting for the other half. The percentage difference between the predicted and observed forces ranged from under 2% to over 100% (Table 19).

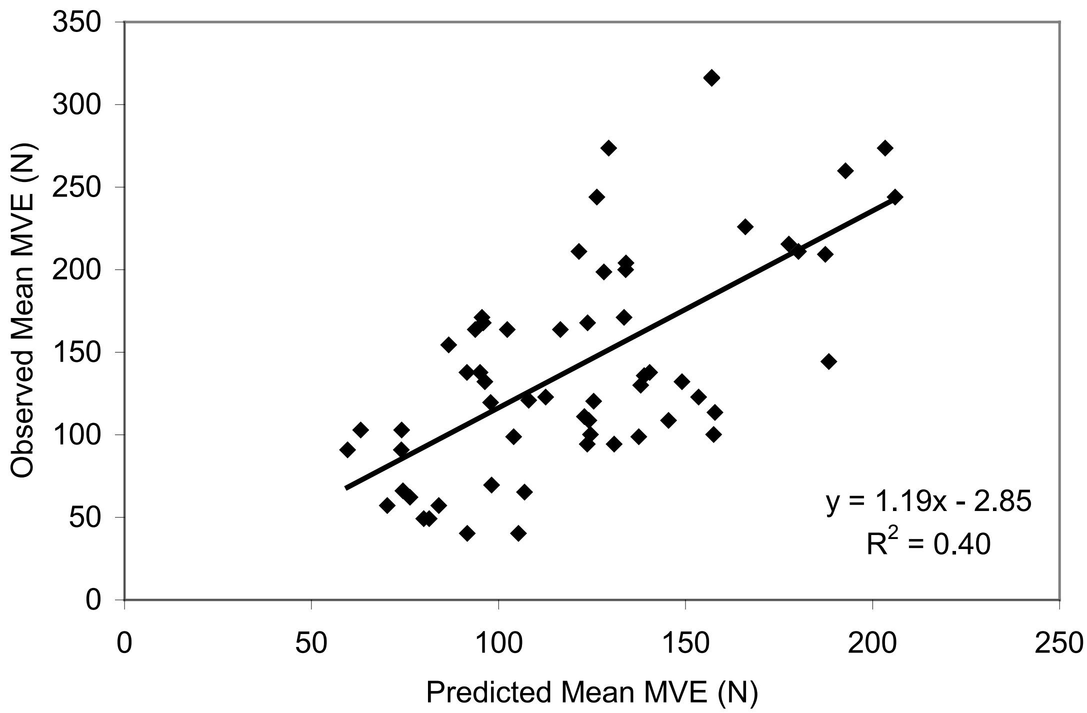

Figure 15. Regression of Predicted 50th percentile MVE values (from 3DSSPP) to Observed MVE values (from Chapter 5)

Table 18. Observed and Predicted MVEs by Task

		Overhead			Elbows Abducted			Waist Bend		Seated Reach		
		Index	Thumb	L. Pinch	Index	Thumb	L. Pinch	Index	Thumb	Index	Thumb	Height
		1	2	3	4	5	6	7	8	9	10	(cm)
Observed	5th F	91.7	105.3	134.0	107.0	138.9	128.1	104.0	137.5	124.1	145.4	156.0
	50th F	81.5	80.0	123.0	74.4	95.0	86.6	63.1	74.1	96.3	149.1	162.2
	95th F	70.3	84.1	98.1	76.4	188.3	102.4	59.6	74.0	91.6	140.4	169.6
	5th M	130.9	123.7	134.0	125.4	187.3	157.0	95.5	133.5	121.5	180.2	170.4
	50th M	124.6	157.5	138.0	108.1	177.6	157.0	95.9	123.8	126.3	206.0	176.6
	95th M	112.6	153.5	157.8	97.9	192.7	166.0	93.8	116.6	129.4	203.4	185.8
Predicted	5th F	40.3	40.3	204.0	65.3	135.8	198.7	98.8	98.8	108.8	108.8	152.0
	50th F	49.3	49.3	111.0	66.0	137.8	154.4	103.0	103.0	132.2	132.2	162.0
	95th F	57.3	57.3	69.5	62.3	144.4	163.8	90.8	90.8	137.7	137.7	172.0
	5th M	94.3	94.3	200.0	120.3	209.3	316.5	171.2	171.2	211.1	211.1	167.0
	50th M	100.1	100.1	130.0	120.9	215.5	315.9	167.8	167.8	243.9	243.9	177.0
	95th M	122.8	122.8	113.5	119.6	259.9	225.9	163.7	163.7	273.7	273.7	188.0
R^2		0.58	0.76	0.17	0.47	0.44	0.68	0.34	0.34	0.40	0.94	
Slope		0.56	0.88	0.15	0.45	0.49	0.37	0.29	0.43	0.15	0.43	
Intercept		58.1	48.7	110.2	57.0	72.5	47.3	47.5	52.4	86.5	92.2	
Limiting Joint		elbow extension	elbow extension	shoulder abduction	elbow extension	shoulder rotation	shoulder rotation	shoulder rotation	shoulder rotation	elbow extension	elbow extension	

5^{th}, 50^{th}, and 95^{th} indicate stature percentile
F: Female
M: Male

Table 19. Percentage difference between predicted and observed mean forces [(predicted – observed) / observed]

	Overhead			Elbows Abducted			Waist Bend		Seated Reach	
	Index	Thumb	L. Pinch	Index	Thumb	L. Pinch	Index	Thumb	Index	Thumb
	1	2	3	4	5	6	7	8	9	10
5th F	-56.1	-61.7	52.2	-39.0	-2.2	55.1	-5.0	-28.1	-12.3	-25.2
50th F	-39.5	-38.4	-9.8	-11.3	45.1	78.3	63.2	39.0	37.3	-11.3
95th F	-18.5	-31.9	-29.2	-18.5	-23.3	60.0	52.3	22.7	50.3	-1.9
5th M	-28.0	-23.8	49.3	-4.1	11.7	101.6	79.3	28.2	73.7	17.1
50th M	-19.7	-36.4	-5.8	11.8	21.3	101.2	75.0	35.5	93.1	18.4
95th M	9.1	-20.0	-28.1	22.2	34.9	36.1	74.5	40.4	111.5	34.6

5^{th}, 50^{th}, and 95^{th} indicate stature percentile
F: Female
M: Male

7.5 Discussion

The 3DSSPP manual states that the model is best used for “the analysis of ‘slow’ movements used in heavy materials handling tasks” (University of Michigan, 1998). It was not clear, nor previously reported, how accurate the model would be for simple hand exertions such as the ones studied here. Regression analysis found that the mean strengths predicted using the 3DSSPP across the ten tasks studied only accounted for 40% of the variance in observed means. Several tasks had fairly high R^2 values, showing that in some cases, the model may be able to accurately predict mean strength for the push tasks studied. In particular, tasks 10 (seated reach, thumb push) and 2 (overhead, thumb push) were predicted with 97% and 76% accuracy respectively. The remaining tasks, however, were not as successfully predicted as indicated by the poor regression fit, small slope, and high percentage difference between predicted and observed. However, it should be noted that for each task, there were only six points from which to form a regression line, limiting the conclusions that can be reached when assessing the tasks individually.

This prediction model was previously tested by Chaffin and Erig (1991) against whole-body exertions tasks and found to predict mean strength with 91% accuracy. Overall, the results of the present study were not able to match this. There are several possible reasons for this discrepancy. First, the model was designed for use in modeling heavy materials handling tasks, but the tasks in this study involved simple, single digit push tasks. This alone may account for much of the variance, as the model assumes the whole hand is used in the exertion. There were three hand positions to select from, prone, semi-prone, and supine; however, there was no single digit selection. Second, in several cases it was difficult to replicate the exact posture, such as in the seated tasks. Other potential sources of error are similar to those discussed by Chaffin and Erig (1991). There also may have been errors in simulating body postures, despite an attempt to match fixture dimensions and photographs of the experimental participants. Another possible limitation is that hand force in the model was assumed to be normal to the pressing surface. Participants were asked to focus their force normal to the transducer; however, there were some minimal forces in other directions. These forces, however small, may affect predicted values.

Although the ability to predict strength data from an existing model would reduce the need for in depth strength testing studies, the results do not support the use of the 3DSSPP model for predicting mean strengths in the ten tasks studied. These single digit exertions appear to be beyond the scope of the model, as it only considered major joint and muscle groups. The complexities of the many joints in the hand and fingers, including the limitations of each joint, may need to be included in this model before it is able to accurately predict forces requiring less than the whole hand.

CHAPTER 8. CONCLUSION

8.1 Summary

Industrial tasks, such as lifting, have been studied for many years, and lifting research has lead to a successful reduction in work related back injuries (Snook, 1985). By measuring strength capabilities in a variety of realistic industrial postures, design recommendations can be made for similar tasks. For more repetitive tasks, derivation of acceptable limits, similar to what has been done in the area of lifting, may be useful in designing and setting guidelines for such tasks. The primary goal of this research was to assess various experimental and existing methods of determining guidelines for manual insertions tasks, which may help to similarly reduce WRMSDs of the upper extremities. This was accomplished by evaluating a relatively new method of determine subjective limits, quantifying the interrelations of MAL and MVE on manual insertion tasks, assessing the effects of gender, task, and hand used on both strength capacity and subjective limits in these insertion tasks, and evaluating the strength capacity data against an existing strength prediction model.

The results from determining MAL evaluation method suggest the self-regulating method described here can produce repeatable estimates of subjective finger force limits and that these limits are insensitive to the analysis method used for estimation of MAL. Both intersession (Chapter 4) and intrasession (Chapter 5) repeatability were high for all evaluation durations investigated, indicating that it may be possible to obtain repeatable values from relatively brief experimental sessions. The subjective limits obtained in the second study corresponded closely to application of the ettxisting guideline from the ACGIH on hand intensive activities to the strength capacity data obtained. This suggests that subjective limits found presently may indeed contribute to a possible reduction in WRMSDs. Additionally, it adds supporting evidence that the subjective method utilized is effective for the determination of force guidelines.

Although the ability to predict strength data from an existing model would reduce the need for in depth strength testing studies, the results did not support the use of the 3DSSPP model for predicting mean strengths in the ten tasks studied. The model focuses on major joint and muscle groups, and single digit exertions appeared to be beyond the scope. The complexities of the many joints in the hand and fingers, including the limitations of each joint, may need to be included in this model before it is able to accurately predict forces requiring less than the whole hand.

8.2 Comparison of Studies

It has been suggested that researchers should use an experimental population that closely resembles the population for which strength data or limits will be applied (Mital, 1987). Within this work, both an industrial and a non-industrial population were tested on the same set of tasks. Female and male students' MVEs were 77% and 69% of industrial workers respectively (Table 20). The average ratio of student to industrial worker MAL was 78% and 61% for females and males respectively (

Table 21). These differences (20% to 40%) are much larger than the 2% to 11% difference found by Mital (1987) who compared students to industrial workers in a lifting task. Another difference of note is the correlation between MAL and MVE for industrial vs. non-industrial populations. R^2 values for the industrial population averaged 0.52 across all tasks, with a range from 0.41 to 0.59. The non-industrial population, however, varied widely amongst the tasks, from a low R^2 of 0.07 to a high of 0.63 with an average of 0.39. This may indicate that for the non-industrial population, there was more difficulty judging forces and extrapolating to a two-hour period. It could also indicate that there may be errors in the MVEs, with participants perhaps not reaching their full strength potential.

Table 20. Mean MVE values (N) for industrial and non-industrial population.

	Industrial		Non-Industrial		Non-Industrial/Industrial Ratio	
Task	Male	Female	Male	Female	Male	Female
1	120.9	76.6	78.3	55.8	64.8	72.8
2	147.8	83.8	99.9	71.9	67.6	85.8
3	145.9	111.4	106.1	70.4	72.7	63.2
4	108.8	77.7	74.6	60.1	68.6	77.3
5	186.3	109.8	135.7	94.5	72.8	86.1
6	160.5	98.3	104.0	87.7	64.8	89.2
7	95.0	64.3	65.5	46.6	68.9	72.5
8	123.0	78.6	87.8	60.4	71.4	76.8
9	126.3	95.9	89.5	67.7	70.9	70.6
10	198.0	143.2	134.7	109.0	68.0	76.1
Mean	141.3	94.0	97.6	72.4	69.1	77.1

Table 21. Mean MAL values (N) for industrial and non-industrial population.

Task	Industrial		Non-Industrial		Non-Industrial/Industrial Ratio	
	Male	Female	Male	Female	Male	Female
1	66.7	41.5	40.8	27.4	61.2	66.0
2	91.5	51.0	56.3	35.7	61.5	70.0
3	90.7	69.7	56.1	47.7	61.9	68.4
4	59.0	42.3	37.0	23.4	62.7	55.3
5	101.5	61.5	56.6	55.0	55.8	89.4
6	91.2	51.2	52.8	47.2	57.9	92.2
7	54.6	38.6	33.7	26.7	61.7	69.2
8	71.9	46.4	50.0	27.3	69.5	58.8
9	75.9	60.8	44.9	43.6	59.2	71.7
10	113.5	80.2	75.2	63.9	66.3	79.7
Mean	81.7	54.3	50.3	39.8	61.8	72.1

8.3 Limitations and Future Research

The main scope of this research was the development of methods and guidelines for manual insertion tasks, but only focused on ten simulated industrial tasks. It is not clear if these results can be generalized to tasks similar, but not identical, to those studied. The lack of a full factorial model reduced the ability to compare the postures and couplings statistically. The differences in force values between tasks can be noted, but it is impossible to pinpoint the source of the variance. A further study that would quantify the specific effects of the various postures and couplings studied is needed.

The poor correlation of MVE and MAL among non-industrial participants, compared with the consistent R^2 values obtained in the industrial participants, suggests that the non-industrial workers may not have been able to accurately evaluate their MAL. This is likely due to unfamiliarity with context of the study, and suggests that the videotape familiarization used here may not have been adequate. In the future, training or several longer practice sessions, may need to be integrated to ensure participants are able to understand and extrapolate sensations to the desired work shift.

The MAL data collection method was only evaluated for repeatability by testing for statistical significance between the means of the respective sessions. This method was adequate for the purpose of this study. There are, however, more formal methods of validating repeatability, such as interclass correlation coefficients, which could also be investigated. To assess reliability, the MAL values obtained should be verified via a series of testing sessions in which the participants work at their selected MAL for an extended period. This could be done for one or two simulated work shifts, to determine if one could work at the selected MAL, but it could also be expanded to a series of work shifts to investigate if the selected MAL would produced early WRMSD symptoms, such as pain and numbness.

Finally, the limitations inherent in the 3DSSPP model were limitations in the study. Two of the tasks could not be accurately modeled, as the software would not allow for a seated position. Additionally, the software only considered major joints and muscle groups, whereas these tasks required large force applied to the smaller joints of the hand and fingers. The complexities of the many joints in the hand and fingers should be included in any model before it can accurately predict forces like those studied here. Further investigation on the capabilities and limits of the hands and fingers would facilitate the use of such a strength prediction model.

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APPENDIX A – MAL INSTRUCTIONS

You should arrive at the maximum level of force that you would feel comfortable doing for a two-hour segment of an eight-hour shift. This should be a force that will allow you to go on to another task at work and still go home at the end of the day without unusual discomfort, pain, or numbness in your finger, hand, wrist, or forearm. Once you feel you have reached an acceptable force, please try to maintain that force level for the rest of the trial.

Do not be afraid to make adjustments. If you feel you are working too hard and could experience pain, numbness, or injury, lighten up for your next press. If you feel you could work a bit harder with out increasing your risk of pain or injury, press slightly harder.

You can never make too many adjustments, but you can make too few. Adjusting your own force level is not an easy task since only you know how you feel.

This is not a contest. We are not looking for the maximum amount of force you can produce; we already have that. Everyone is not expected to do the same amount of work. We want **YOUR** judgment on how hard **YOU** can work without exposing yourself to pain or injury.

APPENDIX B – ASSEMBLY LINE TASK AND SIMULATION EQUIVALENT

Illustrations are provided below for each of the 10 tasks that were simulated in Chapters 4 and 5. For each task, a frame is shown that was obtained from a video recorded during a site visit a major automobile manufacturing facility in the mid-west. Along with each frame, a picture is provided that was taken while a participant performed a simulation of the task using an apparatus constructed specifically for use in the experiment.

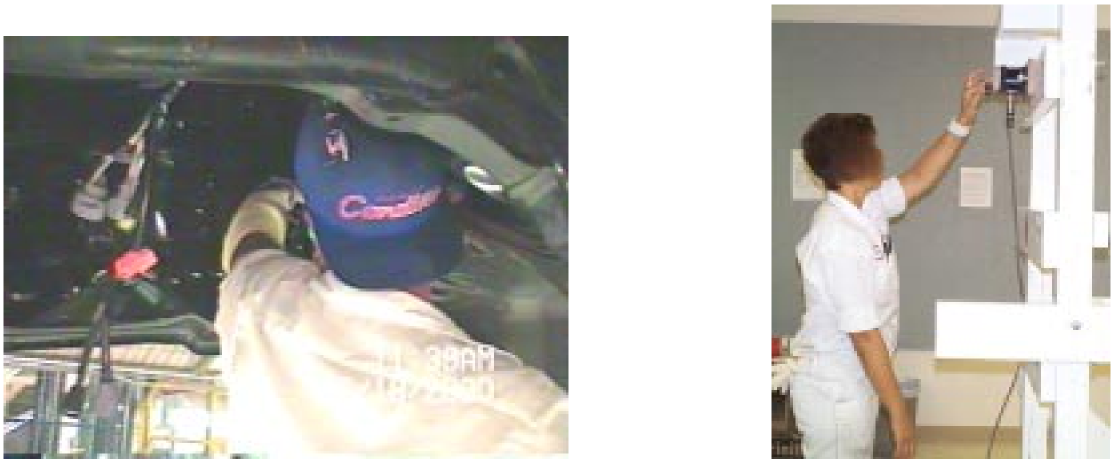

Figure 16. Cabin Harness operation (left) and experimental configuration (right). This was simulated as Task #1: Upright, Overhead Reach, Index Coupling.

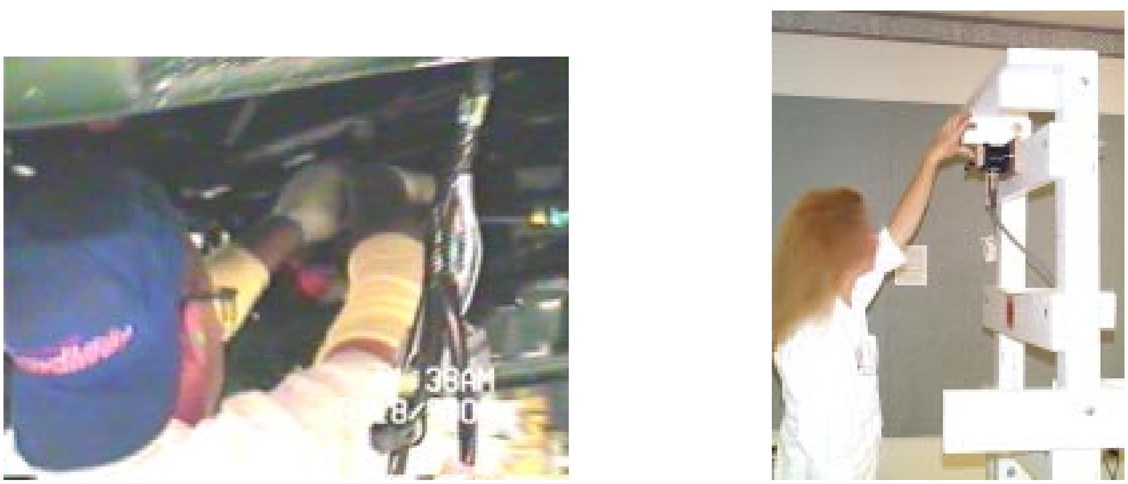

Figure 17. Cabin Harness operation (left) and experimental configuration (right). This was simulated as Task #2: Upright, Overhead Reach, Thumb Coupling.

Figure 18. Fuel Hose operation (left) and experimental configuration (right).
This was simulated as Task #3: Upright, Overhead Reach, Lateral Pinch Coupling.

Figure 19. Floor Harness operation (left) and experimental configuration (right).
This was simulated as Task #4: Upright, Elbows Abducted, Index Coupling.

Figure 20. Floor Harness operation (top left) Steering Column operation (bottom left) and experimental configuration (right).

This was simulated as Task #5: Upright, Elbows Abducted, Thumb Coupling.

Figure 21. Door Line Power Window Install operation (left) and experimental configuration (right).

This was simulated as Task #6: Upright, Elbows Abducted, Lateral Pinch Coupling. (Note: The task was based on an MMP operation that was not videotaped, however the operation shown has a similar posture and coupling.)

Figure 22. Truck Liner operation (left) and experimental configuration (right).

This was simulated as Task #7 and #8: Waist Bend Forward Reach, Index and Thumb Couplings (Thumb shown).

Figure 23. R/S Grommets operation (left) and experimental configuration (right). This was simulated as Task #9 and #10: Seated Forward Reach, Index and Thumb Couplings (Thumb shown).

APPENDIX C – R^2 FOR INDIVIDUAL DIFFERENCE FACTORS

	Overhead			Elbows Abducted			Waist Bend		Seated Reach			
	Index	Thumb	Lat Pinch	Index	Thumb	Lat Pinch	Index	Thumb	Index	Thumb		
MVE	1	2	3	4	5	6	7	8	9	10	Min	Max
Age	0.000	0.003	0.037	0.078	0.017	0.116	0.009	0.007	0.000	0.039	*0.000*	*0.116*
Gender	**0.332**	**0.458**	0.156	0.193	**0.405**	**0.350**	**0.267**	**0.317**	0.200	**0.389**	*0.156*	*0.458*
Stature	0.102	0.038	0.150	0.041	0.303	**0.258**	0.128	0.131	0.171	**0.342**	*0.038*	*0.342*
Body Mass	0.176	**0.297**	0.233	0.112	**0.257**	0.198	0.016	0.164	0.120	0.158	*0.016*	*0.297*
UA Length	0.061	**0.289**	0.057	0.033	0.188	0.139	0.105	0.129	0.100	0.238	*0.033*	*0.289*
LA Length	0.220	**0.393**	0.070	0.149	0.047	**0.266**	0.173	**0.251**	0.194	**0.325**	*0.047*	*0.393*
Shoulder Height	0.165	**0.380**	0.187	0.074	**0.367**	**0.278**	0.173	0.192	0.170	**0.332**	*0.074*	*0.380*
Hours worked prior	0.119	0.099	0.005	0.065	0.224	0.241	0.129	0.215	0.111	0.088	*0.005*	*0.241*
Years Experience	0.008	0.005	0.111	0.000	0.078	0.023	0.029	0.035	0.021	0.057	*0.000*	*0.111*
Min	*0.000*	*0.003*	*0.005*	*0.000*	*0.017*	*0.023*	*0.009*	*0.007*	*0.000*	*0.039*	*0.000*	*0.111*
Max	*0.332*	*0.458*	*0.233*	*0.193*	*0.405*	*0.350*	*0.267*	*0.317*	*0.200*	*0.389*	*0.156*	*0.458*

MAL	1	2	3	4	5	6	7	8	9	10	Min	Max
Age	0.000	0.050	0.000	0.007	0.001	0.030	0.010	0.013	0.003	0.003	*0.000*	*0.050*
Gender	0.229	**0.275**	0.112	0.103	0.247	**0.258**	0.107	0.165	0.078	0.154	*0.078*	*0.275*
Stature	0.089	0.136	0.248	0.016	0.085	0.099	0.023	0.050	0.035	0.124	*0.016*	*0.248*
Body Mass	0.078	0.045	0.050	0.023	0.084	0.106	0.030	0.079	0.055	0.029	*0.023*	*0.106*
UA Length	0.063	0.062	0.056	0.030	0.068	0.046	0.036	0.051	0.033	0.111	*0.030*	*0.111*
LA Length	0.058	0.127	0.042	0.079	0.168	0.157	0.032	0.057	0.043	0.068	*0.032*	*0.168*
Shoulder Height	0.145	0.156	0.054	0.057	0.140	0.143	0.054	0.109	0.065	0.132	*0.054*	*0.156*
Hours worked prior	0.022	0.044	0.027	0.145	0.089	0.049	0.057	0.096	0.042	0.087	*0.022*	*0.145*
Years Experience	0.005	0.088	0.034	0.003	0.037	0.067	0.024	0.058	0.008	0.061	*0.003*	*0.088*
Min	*0.000*	*0.044*	*0.000*	*0.003*	*0.001*	*0.030*	*0.010*	*0.013*	*0.003*	*0.003*	*0.000*	*0.050*
Max	*0.229*	*0.275*	*0.248*	*0.145*	*0.247*	*0.258*	*0.107*	*0.165*	*0.078*	*0.154*	*0.078*	*0.275*

VITA

Hope E. Johnson

Ms. Johnson graduated from Virginia Tech in 1996 with a B.S. in Mathematics. She then went to work for Synetics, Inc. to provide software development support for the Naval Surface Warfare Center, Dahlgren Division on the Aegis program. After two year with Synetics, and another year at GE Financial Assurance, she returned to Virginia Tech to pursue a M.S. degree in Human Factors engineering. While at Virginia Tech, she has served as a teaching assistant and worked on a several projects in the Industrial Ergonomics laboratory. She was awarded a United Parcel Service Fellowship in the Fall of 1999 and a NIOSH fellowship for 2000 and 2001. Upon completions of her degree, she will begin work in the Human Factors Division of the Consumer Product Safety Commission in Bethesda, Maryland.