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A biomechanical investigation of female arm strength.

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A BIOMECHANICAL INVESTIGATION OF FEMALE ARM STRENGTH

By

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ABSTRACT

A BIOMECHANICAL INVESTIGATION OF FEMALE ARM STRENGTH

Christopher Charles Freeman
University of Windsor, 2006

The purpose of the current study was to measure strength and develop regression equations that will predict the maximal capabilities for hand forces exerted in a variety of directions and positions. A biomechanical methodology was utilized to examine 29 non-skilled female subjects exerting maximal forces against a simulation device. Combinations of three heights (head height, shoulder height, waist height), three angles (0°, 45°, and 90° to sagittal shoulder plane), and two reaches (40% and 80% of full reach) were tested for maximal force in six directions (push forward, pull backward, push up, push down, medial, lateral). Electromyography was also measured from arm and shoulder muscles while performing the tasks. Repeated measures ANOVA, with Tukey's HSD tests, were used to determine significance within the measured variables ($p<0.05$). Analysis of data indicated that height, angle and reach all had significant effects on the amplitude of the force produced. Subjects produced the maximum amount of force (approximately 285 N), in the push down direction at high height. Medium height exertions were the highest in four of six directions. Strength tended to decrease with increasing angle, in four of six directions, and increased reach in four of six directions. Using the force data, 12 regression equations were developed to predict average maximum force for the working female population. For each direction, an equation was developed for exertions ≥ shoulder height and for exertions ≤ shoulder height. These equations use inputs of various combinations of distance in the vertical, horizontal and lateral direction from the shoulder. The regression equations resulted in r^2 values ranging from 86.0% (lateral) to 98.9% (medial) and RMS errors ranging from 8.0% (push down) to 3.0% (medial). With a mean r^2 of 94.6% and RMS %Error of 5.4%, the equations produced very accurate predictions. Using a correction factor of 0.808, each equation can be used to predict the maximum recommended force for 75th percentile of females. In addition to the force results, electromyography results provided information on muscle activity during the exertions in all postures.

DEDICATION

First and foremost I would like to dedicate this thesis to my wife, Katherine Freeman. She has given me unending love, support and encouragement. I could not have completed this thesis and my Master of Human Kinetics degree without her supporting me. She is my best friend and I am so glad to share this achievement with her. Thank you for supporting me and helping me to reach this milestone in my life. I love you. This work is for you.

I would also like to dedicate this work to my parents, Gerald and Debra Freeman. They have always encouraged me in every endeavor, including my graduate degree. This project represents the work ethic and perseverance that my parents instilled in me throughout my life. I am so grateful for my parents and without them this would not have been possible. Thank you for your love, words of encouragement and all you have done and continue to do for me.

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LIST OF ABBREVIATIONS

3D SSPP: 3 Dimensional Static Strength Prediction Program

3-D: 3 Dimensional

A/D: Analogue to Digital

ANOVA: Analysis of Variance

BB: Biceps Brachii

C7: 7^{th} Cervical Vertebra

DA: Anterior Deltoid

DL: Lateral Deltoid

EMG: Electromyography

EMG_{PK}: Peak EMG amplitude

H: Horizontal distance from acromio-clavicular joint

H_H: High height or head height

H_L: Low height or waist height

H_M: Medium height of shoulder height

L: Lateral distance from acromio-clavicular joint

MVC: Maximum Voluntary Contraction

OSHA: Occupational Safety and Health Administration

R_1: 40% reach

R_2: 80% reach

RMS: Root Mean Square

RULA: Rapid Upper Limb Assessment

sEMG: Surface Electromyography

TB: Triceps Brachii

TLV: Threshold Limit Value

TR: Upper Trapezius

V: Vertical distance from acromio-clavicular joint

WSIB: Workplace Safety and Insurance Board

Chapter 1: INTRODUCTION

1.1Background

Workplace injuries have been, and continue to be, a major issue in the workforce today. They have been associated not only with debilitation of the worker but also with a large monetary cost to employers. In 2002 there were 361,179 claims registered in the province of Ontario (WSIB of Ontario, 2003). These claims range from neuropathies, strains, sprains, burns, to infections, crushing injuries, and amputations. In 2003, in the United States, there were approximately 4.1 million recorded occupational injuries (United States Department of Labor, 2004). Fully 2.3 million (56%) of the recorded cases resulted in days lost from work in 2003.

Not only are the numbers of injuries and registered claims important to companies, the cost of these claims is also very important. According to the National Academy of Social Insurance (Thompson Williams *et al.*, 2004) $53.4 billion was paid out in workers compensation claims in the United States in 2002. This value has increased from $43.4 billion in 1999, and $41.8 billion in 1996 (Mont *et al.*, 2001). When analyzing the injury rates and the cost data, an inverse relationship can be seen. Even though the number of cases recorded per 100 workers has decreased, the amount of dollars paid out in workers compensation claims over the same period has increased. In addition to direct cost, the indirect cost must be considered as well. The statistics above do not include costs such as compensating higher wages to workers for job risks, redundant hiring to insure against workplace injury, lost worker productivity, training other workers to replace injured workers, decreased moral, overtime costs and others (Reville *et al.*, 2001). What has become evident is the enormous cost that occupational injuries levee on employers. Other organizations, such as insurance companies, and government agencies, also suffer large costs. For these reasons, and others, the effort to decrease workplace injuries has become very important.

Further analysis of injury data results in the conclusion that not all body parts are affected to the same degree. According to the Ontario WSIB's Annual Report (2003) in 2002, 24.3% of all recorded lost time injuries were to the upper extremities (arm, forearm, wrist, hand). What's more, the shoulder accounted for an additional 6.1% of all recorded lost time injuries such that this combined group was injured with higher frequency than any other grouping at 30.4% of all recorded lost time injuries. The back ranks second at 29.6%, the majority of which can be attributed to the lumbar region at 19.9%. Even though much research has focused on determining ways to alleviate or limit risk factors, upper extremity injuries still occur. In fact, when examining the injury data in Ontario, it appears that there has been little to no decrease in occupational upper extremity injuries over at least the last six years (WSIB of Ontario, 2003). There may be many different reasons for this, such as strength changes and anthropometric differences in workers, the inability to modify older facilities, continuing design change in certain industries, and other research related factors such as inappropriate study design.

There is a large body of research that has examined the different work related injuries that may occur in the shoulder and upper extremities. Injuries such as tendonitis, tenosynovitis, thoracic outlet syndrome and bursitis have been studied and documented widely (Abe *et al.*, 1999; Ambrad-Chalela *et al.*, 2002; Armstrong *et al.*, 1987; Brantigan and Roos, 2004; Bureau *et al.*, 1996; Calabro, 1982; Chengelis *et al.*, 1994; Cibrario, 1997; Drochner, 1997; Dunant, 1979; Goldstein *et al.*, 1987; Mani and Gerr, 2000; Punnett *et al.*, 2000).

Occupational injuries to the upper extremities and shoulder have been linked to risk factors such as poor posture, repetitive motion and large forces (Anton *et al.*, 2001; Das and Wang, 2004; Forde and Buchholz, 2004; Haslegrave *et al.*, 1997; Mcatamney and Corlett, 1993; Mogensen and Stobbe, 1985; Moore and Garg, 1995; Muggleton *et al.*, 1999; Putz-Anderson, 1992). In support of the effort to reduce workplace injuries, researchers have conducted numerous studies focused on the above mentioned risk factors: posture, repetition and force. Large amounts of data have been gathered from these studies and, in some cases, used this to set threshold limit values (TLV's) (Fernandez *et al.*, 1991; Potvin *et al.*, 2000; Snook, 1978; Snook and Ciriello, 1991). Cooperation between researchers working with the National Institute for Occupational Safety (1981) have resulted in limits for spinal compression during lifting. Other studies, that have set limits for tasks such as lifting, lowering, pushing and pulling, are Snook (1978), Snook and Ciriello (1991) and Mital *et al.* (1993). Researchers have developed tools to be used in an effort to aid employers and Ergonomists. Tools such as the Strain Index (Moore and Garg, 1995) and the Rapid Upper Limb Assessment (RULA) (Mcatamney and Corlett, 1993) are used to evaluate upper limb postures and injury risks. In spite of these and many other efforts, workplace injuries continue to be a problem in industry.

Another related area of research examines muscular strength. Strength studies have been conducted for various body parts and muscle groups in an effort to better understand human strength capabilities (Anton et al., 2001; Das and Wang, 2004; Essendrop et al., 2001; Garg et al., 2002; Haslegrave et al., 1997; Keyserling et al., 1980; Roman-Liu and Tokarski, 2005; Stobbe, 1982). There are, however, no current all encompassing published databases containing a sufficient amount of upper limb strength data. In strength testing, there are often many different postures tested and numerous different study designs used by the researchers. Furthermore, from the existing strength data, extrapolations and assumptions have been made to try and determine force capabilities in untested, and/or under-tested postures. The combination of former issues (anthropometric differences in workers, the inability to modify older facilities, and continuing design change in certain industries) and the latter issues (strength testing discrepancies), have made it rather difficult to eliminate risk factors leading to upper extremity occupational injures.

Occupational injuries are also broken down by industry sector. One very specific sector that has a large number of recorded lost time injuries is the automotive sector. In Ontario alone 6.1% of all occupational lost time injures occurred in the automotive industry (WSIB of Ontario, 2003). It should also be noted that the manufacturing industry accounted for 18.2% of all lost time injuries in the same year and that some of the manufacturing industry is related to automotive, such as tier three suppliers. In 2003 in the United States, 21% of all workplace injuries were recorded in the manufacturing sector (United States Department of Labor, 2004). The automotive industry is included in this figure. The combination of the high percentage of injuries that occur in the manufacturing/automotive industry, along with the high percentage of injuries to the upper limb, has lead to many studies on the upper limb and related injuries.

In the automotive industry many tasks are performed by employees with hand tools and still others by employees with no mechanical assistance. Some tasks performed by employees require them to exert a force against an object in a certain location. Some examples of this are tasks such as trim installation, hose insertions, electrical connections, manual part manipulation etc. These tasks require a person to apply a hand force in a given direction with a certain amount of force in a specific location a number of times per day. These tasks may also require activation of various muscles in the upper extremity and may be performed in postures that are non-neutral. These tasks are often performed on an assembly line. The fact that these tasks exhibit characteristics of all three lead one to conclude that there is a real potential for injury in these job tasks.

Currently, the automotive industry employs various ergonomic tools in order to evaluate, set threshold limits and reduce some or all of the risk factors. Two of the more commonly used tools are 3-Dimensional Static Strength Prediction Program (3D SSPP) software (The University of Michigan Center for Ergonomics, 2001) and WatBak (Norman *et al.*, 1998). 3D SSPP software allows the analyst to input anthropometric scaling, posture and external force values which it uses to calculate numerous different outputs. These outputs include, but are not limited to, compression forces, joint moments, limiting muscle or joint, and strength capabilities. Companies use this tool to set acceptable limits or threshold limit values for their work tasks. A deficiency with these software programs is simply that the strength data on which the upper extremity portion is based, is not very extensive.

The 3D SSPP data is based on work done by various researchers from the early 1950's to the early 1980's (Clark, 1966; Elkins et al., 1951; Schanne, 1972; Singh and Karpovich, 1968; Stobbe, 1982; Williams and Stutzman, 1959). Large portions of the data come from Stobbe (1982) who tested strength for six shoulder exertions and two arm exertions. In these tests, subjects exerted forces against a resistance not placed at the hand but at either the distal end of the humerus or the proximal end of the forearm. The force recordings at these positions, as well as strength data from other studies, were then used to calculate the maximum forces that could be exerted at the hand. The overriding issue with this is that, between the shoulder and the hand, there are four degrees of freedom in the model (3 at shoulder, 1 at elbow). This creates a situation in which there is susceptibility to error at four levels, with each additional error potentially compounded by the previous one.

Another tool used extensively by the automobile industry for analysis is 4-dimensional WatBak (Norman *et al.*, 1998). This software program is used as a biomechanical modeling program that provides the analyst with lumbar loads, compression, reaction shear, joint shear, cumulative loads, and calculates injury risk for various body actions. The data on which this program is based are essentially single references for a given movement. There were two references for the shoulder strength data (Koski and Mcgill, 1994; Lannersten et al., 1993) and one for the elbow strength data (Askew *et al.*, 1987). This program exhibits a similar deficiency to those identified of 3D SSPP. Most of the values are extrapolated from a few surrounding values, leaving much room for error as well as the compounding of error.

The data collected by Stobbe (1982) and his counterparts proved invaluable, it is not comprehensive enough to base the current three dimensional strength prediction software on entirely. Further research must be conducted to determine what the strength capabilities are, between and around the locations previously tested, as well as what the strength values are about three axes.

In summary, there is a continuing increase in upper extremity injuries resulting in lost work time. These injuries can be both debilitating and costly. Furthermore, the current ergonomic tools, used specifically by the automotive industry, are not capable of providing adequate and accurate information to job designers and analysts. Tools like 3DSSPP, are the industry standard and provide the best guess for ergonomists. These tools are used to calculate the maximum forces at the hand but are based on individual joint strength values. These strength values from the shoulder and the elbow are summed and may lead to larger errors when given at the hand. The above mentioned tools are based on data that does not account for all movements or postures. This situation leads to job analyses which may not be accurate. This is likely due to the fact that in all of the strength tests, values were not tested at the hand, which is where external forces are applied during production tasks. Further research is needed to determine what the maximal forces are that can be exerted at the hand. This information may then be used to develop a model(s) ensuring appropriate force requirements are set on work tasks.

1.2 Statement of Purpose

The purpose of this study was to measure arm strengths and muscle activity as well as to develop regression equations that will predict the maximal capabilities for hand forces exerted in a variety of directions in a variety of positions. Utilizing biomechanics, and electromyography, maximal strength will be determined for six exertion directions (exert up, exert down, exert right, exert left, push out and pull in), four different arm angles (across midline, sagittal shoulder plane, 45° to sagittal shoulder plane, and frontal plane), three different heights (top of head, shoulder height, waist height), and two reach distances (80% arm reach and 40% arm reach) during maximal force exertions simulating those typically observed in industry.

1.3 Hypotheses

1. *Strength data will show a statistically significant interaction ($p<0.05$) between angle and direction. Post hoc analysis of these variables will show the highest acceptable limit will be displayed in the sagittal shoulder plane (0°) during pushing. This will be greater than all other directions and angles.*

Postures deemed as non-neutral have been identified as a risk factor and have been shown to potentially cause injuries (Anton et al., 2001; Haslegrave et al., 1997; Putz-Anderson, 1992; Roman-Liu and Tokarski, 2005). The increase in injury risk can lead to a decrease in force production due to inhibition. In cases where there is a potential for injury, the body may inhibit large amounts of force exertion, thereby protecting the body. Different postures have different effects on structures in the shoulder joint. Furthermore, different muscles are used when exerting forces in different directions. The highest amounts of force exerted in all of the upper extremity postures tested by Stobbe (1982) were found in the horizontal forward exertion shoulder strength test. According to Haslegrave *et al.* (1997) some of the highest forces recorded were exerted when the subject was pushing at shoulder height.

2. *Bio-mechanic information will show a statistically significant interaction ($p<0.05$) between reach and height. Further post hoc analysis will show that shoulder strength at 80% reach will be greater than at 40% reach distance and that the greatest acceptable levels will be in medium height.*

Reach distance has been found to be a major predictor of strength values in testing. A study conducted by Anton *et al.* (2001) found that the closer reach distance provided the subject with an advantage and more force could be exerted when tasks were located close to directly overhead. This, however, is not the case when working at or below shoulder level. In a study by Haslegrave *et al.* (1997) it was found that in overhead exertions, as the reach distance was decreased, the amount of force subjects were capable of producing also decreased. This study also demonstrated that of all the testing locations, far reach at shoulder level (or medium height) provided some of the highest force levels.

3. *It will be possible to develop multiple regression equations to allow for the accurate prediction of maximal hand forces based on inputs of height, reach and arm angle.*

Given the independent variables such as the height of exertion, the length of reach, and the angle of exertion in the transverse plane, regression equations will be calculated for each of the six directions. Using a software program called Stats View (SAS Institute Inc., 1997) a multiple regression analysis will be conducted to determine the involvement of each independent variable tested. Each variable will be weighted the appropriate amount to generate values with minimal variance to the values recorded during testing. These values, when compared against each other will produce both a low RMS error as a percentage of the maximum value (less than 10%) and a high r^2 value (above 95%). Regression equations have been used by many researchers to predict weights, forces and other outputs. Some of the most notable regression equations examined acceptable lifting task loads (NIOSH, 1981; Potvin, 1997). With the varying use of arm, rotator cuff, and trunk musculature in the actions being tested in the current study it is likely that there were regression equations developed for each direction (up, down, right, left, push and pull). Predicted values were compared to recorded values from the current experiment.

Chapter 2: LITERATURE REVIEW

2.1 Upper extremity anatomy

2.1.1 Bone

The appendicular skeleton consists of the shoulder girdle, arm, forearm, wrist and hand (Figure 1). The function of the shoulder girdle is to attach and secure the bones of the upper limbs to the axial skeleton. It is composed of the scapula and the clavicle. The clavicle articulates medially with the manubrium of the sternum and articulates laterally with the acromion of the scapula. These three bones (clavicle, sternum and scapula) form the sternoclavicular joint and the acromioclavicular joint respectively. On the lateral portion of the scapula is the glenoid fossa where the head of the humerus articulates. At the distal end of the humerus the radius and ulna meet forming the elbow. Further, at the distal portion of the forearm there are eight carpal bones which connect distally to the metacarpals and phalanges (Tortora, 2005).

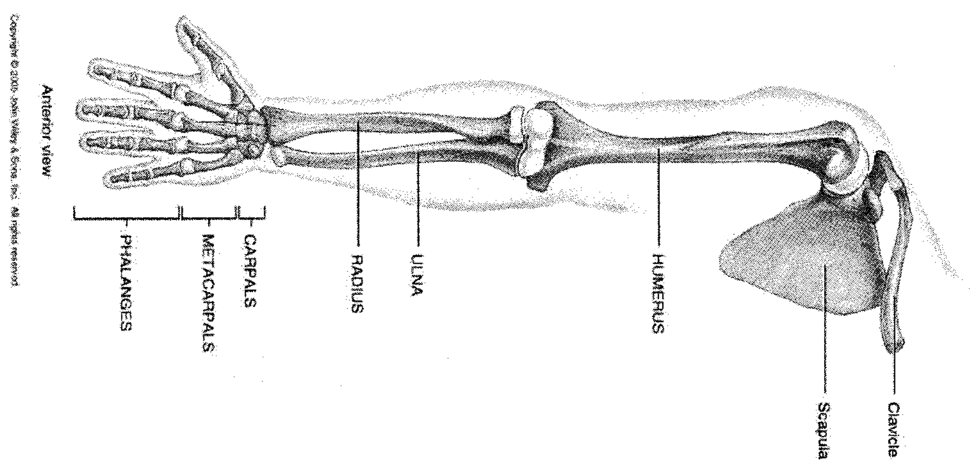

Figure 1: Appendicular skeleton. Diagram of arm, forearm, wrist, and hand bones (Tortora, 2005).

2.1.2 Muscle

The shoulder girdle has a very complex system of muscles. There are a few distinct muscle groups that will be listed here. The anterior thoracic muscles consist of the pectoralis minor and serratus anterior (Figure 2). These muscles, as a group, help to stabilize the shoulder girdle, abduct the scapula and rotate it both upwards and downwards. Neither of these muscles crosses the shoulder joint. The serratus anterior, however, is important in horizontal movements of the arm such as punching and pushing.

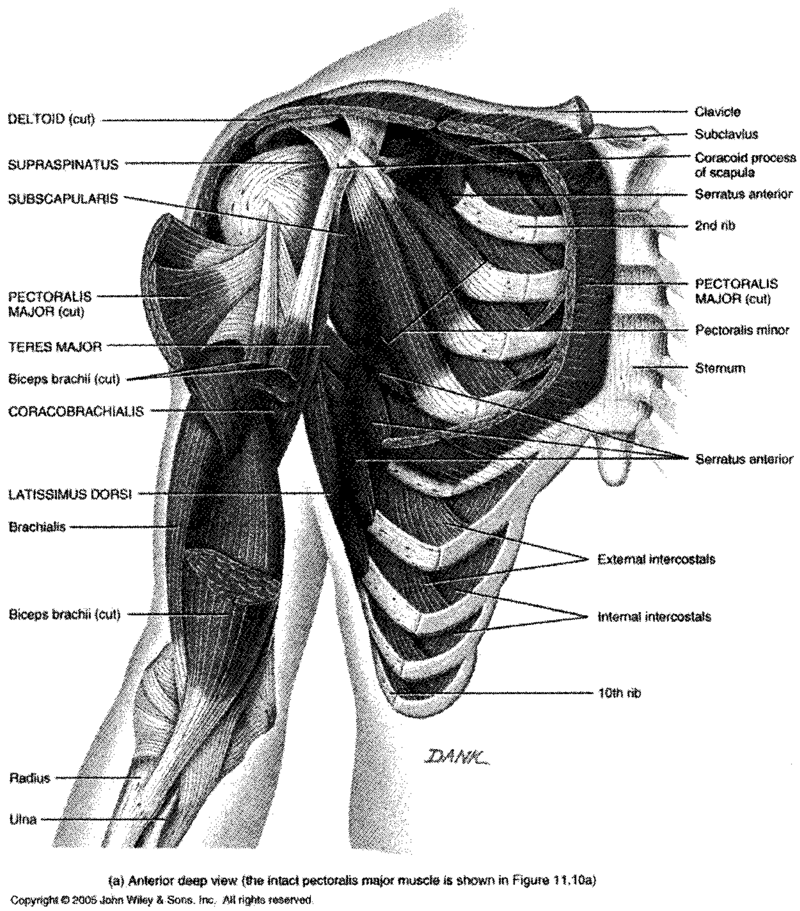

Figure 2: Anterior thoracic muscles: serratus anterior and pectoralis major. Anterior axial muscles: pectoralis major and latissimus dorsi. Scapular muscle: deltoid. (Tortora and Grabowski, 2003)

The second muscle group at the shoulder is the posterior thoracic muscles. This group consists of the trapezius, levator scapulae, rhomboid major and minor (Figure 3).

The latter three muscles serve, as a group, to stabilize, elevate, adduct the scapula and rotate it downward. The trapezius, due to its large origin, performs a number of actions. The trapezius rotates the scapula upwards, elevates, stabilizes the scapula, adducts and depresses the scapula. None of the above mentioned muscles in this group cross the shoulder joint but provide a solid foundation for arm movements.

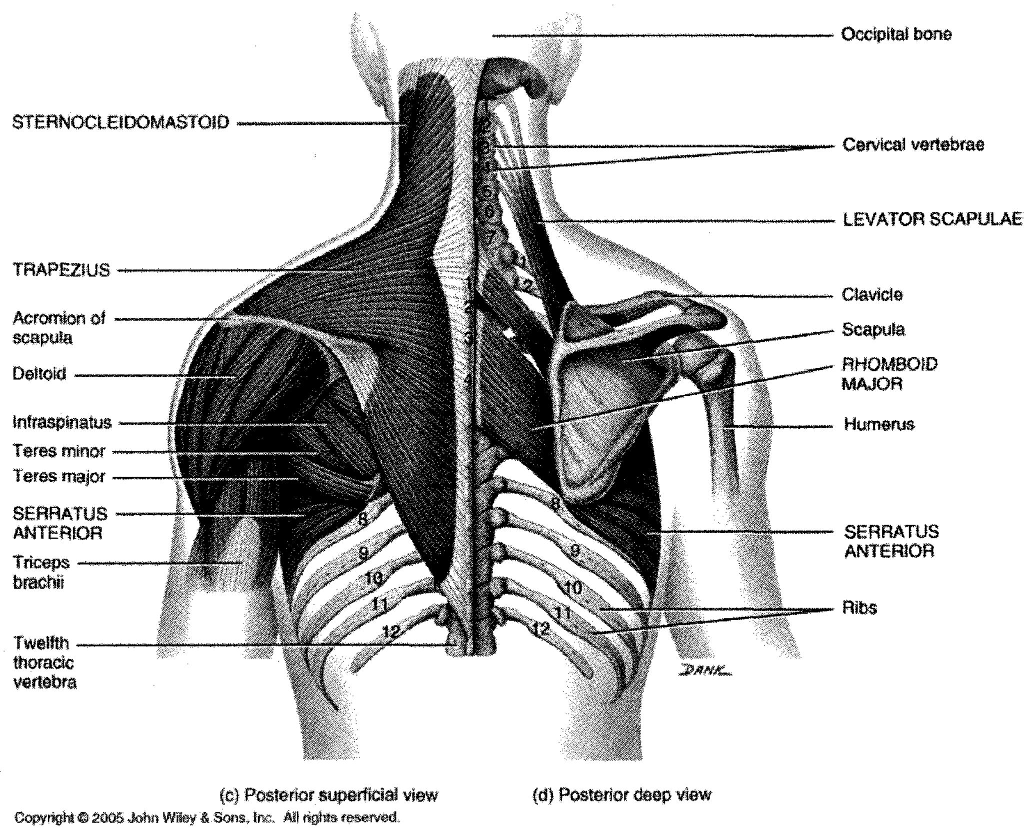

Figure 3: Posterior thoracic muscles. Trapezius, levator scapulae, rhomboid major and minor. (Tortora and Grabowski, 2003)

The third group of muscles are those that act directly on the humerus. These muscles are broken down into two different groups, the axial muscles and the scapular muscles. The axial muscles are the pectoralis major and latissimus dorsi (Figure 2). The pectoralis major adducts, medially rotates and flexes the arm and it can also extend the flexed arm to the side of the trunk. The latissimus dorsi extends, adducts and medially rotates the arm at the shoulder joint. It also pulls the arm inferiorly and posterior.

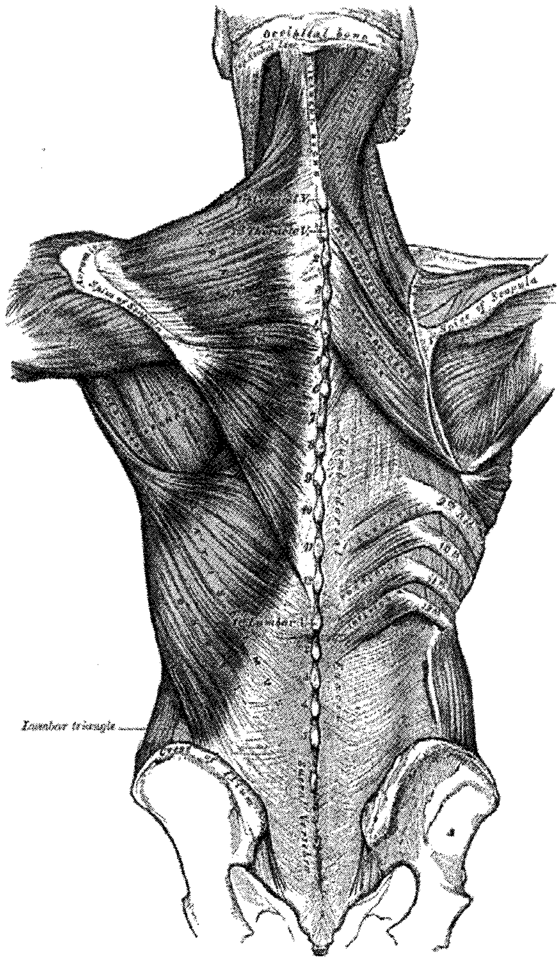

Figure 4: Posterior scapular and trunk muscles. Teres major, latissiumus dorsi, infraspinatus, supraspinatus. (Gray, 2000)

The major muscle of the scapular group is the deltoid (Figures 2, 3, 4). This muscle has a large origin which allows for a number of different actions. Lateral fibers abduct the arm at the shoulder, where anterior fibers both flex and medially rotate the arm at the shoulder joint. Posterior fibers extend and laterally rotate the arm at the shoulder joint. The other muscles in this group all help contribute to the deltoid's actions. The muscles are; the subscapularis, supraspinatus, infraspinatus, teres major, teres minor and coracobrachialis (some shown in Figure 4). All of the deltoid's actions can be accounted for by one or more of these other muscles. All of the muscles in this group cross the shoulder joint.

The fourth group of muscles involves those that move the radius and/or ulna. These muscles are divided into four subsections. The first are those muscles which flex the forearm: biceps brachii, brachialis, and brachioradialis (Figure 5).

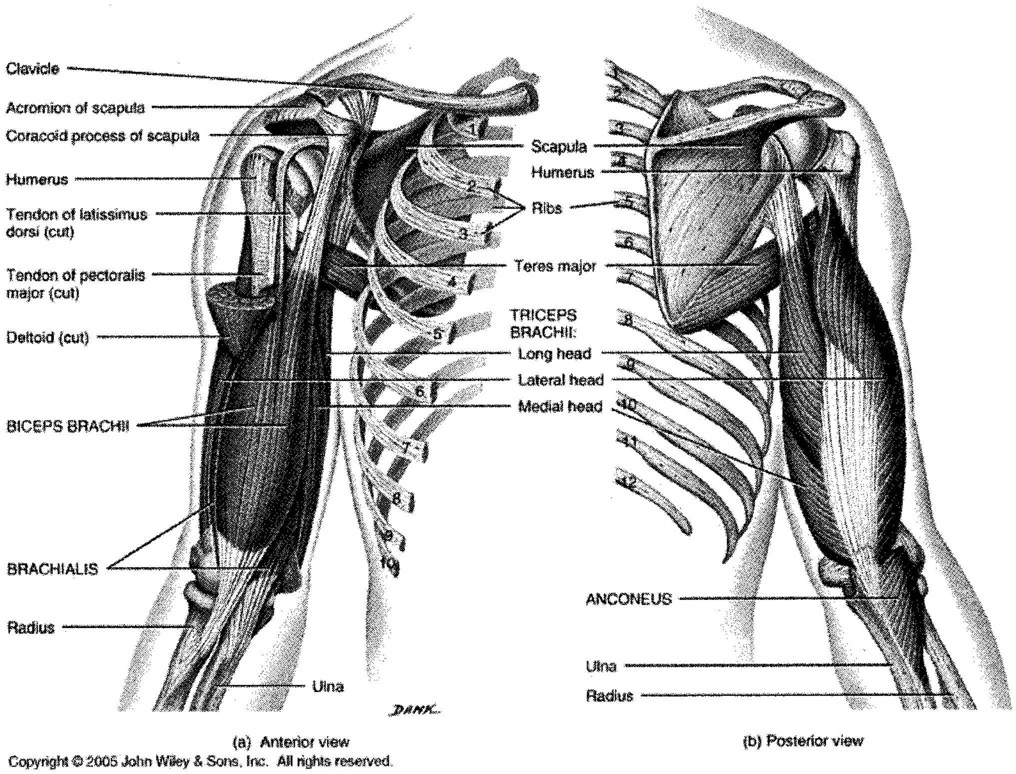

Figure 5: Muscles acting on the forearm. Biceps brachii, brachialis, brachioradialis, triceps brachii, and anconeus. (Tortora, 2005)

Two of the three muscles (brachialis and brachioradialis) start on the humerus and insert on the forearm on either the radius or ulna. The third muscle, the biceps brachii, crosses two joints, the shoulder and the elbow. Originating on the scapula and inserting on the radius in the forearm, the biceps brachii also creates flexion of the arm at the shoulder joint. The second subsection is the forearm extensors, which include the triceps brachii and the anconeus. These muscles cross the elbow joint and cause extension of the forearm at the elbow joint. The third and fourth subsections are the forearm pronators and forearm supinators.

Contained within the forearm are a large number of muscles which produce all of the actions at the hand and wrist. These muscles create, flexion, extension, ulnar and radial deviation (Figure 6). These muscles cross the joints in the wrists and phalangeal joints (Tortora, 2005).

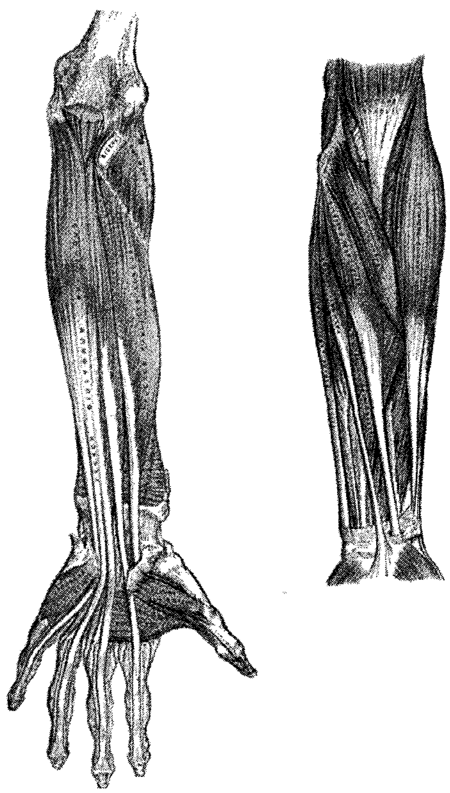

Figure 6: Posterior and anterior superficial forearm extensors and flexors. (Gray, 2000)

2.2 *Risk Factors*

Shoulder and upper extremity disorders were addressed as early as the 1700s by Bernardino Ramazzini. This 18th century author is regarded by some to be the father of modern occupational or industrial medicine (Winkle and Westgaard, 1992). In the 1950s, work-related upper limb complaints were increasing in Japan (Winkle and Westgaard, 1992). According to the WSIB of Ontario's annual report (2002), work-related injures to the upper extremities and shoulders combined to result in 30.4% of all reported lost time injuries in Ontario in 2002. When combined, these two body parts constitute the body location resulting in the highest incidence of lost time injuries. This value was found to be greater than injuries to either the back or the lower extremities.

Due to the increasing problem that work related upper extremity injuries presented, research was needed in this area. In the early 1990s two of the tools that were developed were to evaluate work related upper extremity disorders. The Rapid Upper Limb Assessment (RULA) (Mcatamney and Corlett, 1993), and the Strain Index (Moore and Garg, 1995) were developed to evaluate and prioritize risk factors associated with upper extremity disorders. It is believed that musculoskeletal disorders are not caused by acute incidents but are developed over time due to repeated micro trauma (Putz-Anderson, 1992). The most common risk factors found in the literature are force, repetition, and posture (Anton et al., 2001; Mcatamney and Corlett, 1993; Moore and Garg, 1995; Szeto et al., 2002; Winkle and Westgaard, 1992). Many studies have suggested that prolonged work in awkward postures and/or heavy manual materials handling can lead to or accelerate musculoskeletal disorders (Lutz et al., 2001; Nussbaum et al., 2001; Wiktorin et al., 1993). The combination of these risk factors can lead to a cumulative trauma disorder (Putz-Anderson, 1992). Further research has found that upper limb strength is affected by limb angles and positions. In addition, it was found that strength decreases in certain postures (Roman-Liu and Tokarski, 2005).

2.2.1 Neck

Upper extremity injuries, including the neck, suffered at work can be inflammatory and degenerative in nature. This can result in pain and discomfort for the worker, and affect their ability to perform their job. Furthermore, individuals who suffer from chronic neck pain also often exhibit other symptoms such as headaches with pain in the jaw and thoracic region. Some of the symptoms that accompany neck pain are sometimes not physiologically explainable, such as Fibromyalgia (Ferrari and Russell, 2003). These injuries can be caused by the same risk factors that were mentioned above. There is strong evidence to suggest that force, posture and repetition are physical, work related risk factors for neck and shoulder disorders (Buckle and Devereux, 2002). There has been much research to suggest that working with the head bent forward can lead to both shoulder and neck pain (Szeto *et al.*, 2002). In addition, it has been found that the duration of sitting, twisting and bending the trunk in working postures can lead to neck pain (Krause *et al.*, 1997). Neck pain remains a costly, common cause of disability and a significant contributor to absenteeism and lost productivity (Makela *et al.*, 1991).

In the manufacturing industry, there are many jobs which necessitate neck flexion. Many of these tasks are quality control or inspection tasks. Some researchers have conducted studies to attempt to verify the cause and reduce the pain and discomfort associated with the forward flexion of the head and neck. It was hypothesized that the utilization of mirrors to inspect parts instead would reduce neck pain and discomfort by reducing the degree of bending the neck forward (Lutz *et al.*, 2001). It was found that using one or more mirrors provided some relief from both shoulder and neck pain when compared with the traditional method of inspection.

Other causes of neck and/or shoulder pain are somewhat less obvious. Repetitive hand and finger movements have been found to not only contribute to but are consistently linked, with neck and shoulder disorders (Fredriksson *et al.*, 2000). Psychosocial factors, as well as the perceived workload, have been found to be factors for women developing these disorders. Whereas physically demanding work and segmental vibration were found to be factors for men developing neck and shoulder disorders.

2.2.2 Shoulder

Injuries resulting in lost time to the shoulder accounted for 6.1% of all injuries in the province of Ontario in 2002 (WSIB Ontario Annual Report). Table 1 shows worker's compensation board information for the province of British Columbia (Workers Compensation Board of British Columbia, 2003).

Table 1: Shoulder disorder claim information for British Columbia, 1983-2002.

Disorder	# of Claims	# Days Lost/Claim	Thousands of $ paid /claim
Bursitis (repetitive motion)	8,708	83	10.2
Tendonitis (repetitive motion)	25,539	56	12.6

Injury statistics in Great Britain indicate that injuries to the upper extremities and neck have a prevalence of approximately 448,000 (Health and Safety Executive, 2004). According to the Occupational Safety & Health Administration of the United States, in 2002 there were 34,351 reported cases of overexertion injuries to the upper extremities and 42,356 reported cases of repetitive motion injuries to the upper extremities. In addition, there were 6,497 reported cases of tendonitis. Furthermore, of all upper extremity injuries suffered at work resulting in lost work days, fully 23% of recorded cases were longer than 31 days of missed work. This percentage was greater than all other categories, leading one to believe that there are more serious injuries suffered to the upper limbs than non-serious injuries (Occupational Safety & Health Administration, 2003).

There are three general types of musculoskeletal injuries that can occur in the shoulder: tendon disorders, nerve disorders or neurovascular disorders (Putz-Anderson, 1992). Tendonitis is one of the more common forms of injury. It is simply the inflammation of the tendon that arises from repeated tensing of the tendon. Limited recovery time between cyclic consecutive work tasks has been found to be highly physically demanding and can lead to muscle soreness and tendon inflammation (Luopajarvi *et al.*, 1979). Tendonitis of the rotator cuff tendons, which aid in inward and outward arm rotation, is one of the more common types. This is partially due to the small bony passage bordered by the humerus and the acromion through which some of them pass. Working with the arm(s) elevated, maintaining static contractions and repetitive motions without adequate rest between motions, have been noted as causes of tendonitis. The lack of blood flow and the friction often lead to inflammation of the tendon causing pain and discomfort (Hagberg, 1996; O'Neil et al., 2001).

Bursitis is another overexertion injury that can occur at the shoulder joint. Repeated exertion of a muscle at a joint can cause inflammation of the bursa, which is called bursitis (Tortora, 2005). A bursa is a fluid filled sac and can be found in areas of the body where tendons and muscles articulate over bony prominences. One such bursa is the subacromial-subdeltoid bursa, found in the shoulder between several local tissues. Direct trauma, chronic overuse and systemic disorders can lead to bursitis. Chronic overuse can be a result of working with arms elevated, overhead work, as well as limited rest and recovery time (Bureau *et al.*, 1996; Celiker, 2001). Another common overuse disorder at the shoulder is thoracic outlet syndrome. This is characteristic of entrapment of the brachial plexus, by compressions, twisting and/or stretching within the thoracic outlet. Symptoms such as sensory disturbances, motor disturbances, stiffness, pain and numbness in the region, as well as vascular compression often occur. (Abe *et al.*, 1999; Roos and Wilbourn, 1999). This condition is usually made worse by arm elevation or carrying heavier objects such as luggage or grocery bags. The combination of these symptoms would, in many cases, lead to a decreased ability to exert forces due to pain and possible motor disturbances.

Work performed in non-neutral or poor working postures has been found to lead to musculoskeletal injuries. Anton et al. (2001) concluded that, when working overhead, an extended reach can increase the risk of injury. It is better to perform the work directly overhead and in close proximity to the body, decreasing shoulder stress and injury risk. Another study concluded that upper limb angles at the shoulder, elbow and wrist can have great impact on the amount of force that can be exerted in a given direction (Roman-Liu and Tokarski, 2005). It was found that there are seven different joint angles which affect the ultimate strength capability of the upper limb. Angles providing the greatest strength advantage for lifting force, however, were different than that for supination torque. Garg, Hegmann, Schwoerer and Kapellusch (2002) found that there is an increase in muscular endurance when the shoulder is flexed between 120° and 150°. According to the results of that study it appears that, if a task requires hands to be at or above shoulder level, it is better that it is higher than lower when in forward shoulder flexion.

2.2.3 Elbow

The elbow is also susceptible to various disorders and injuries. Medial and lateral epicondylitis are common injuries suffered at the elbow. They are often termed golfer's and tennis elbow respectively and are often classified as overuse syndromes (Pienimaki *et al.*, 2002). Lateral epicondylitis is characterized by epicondylar tenderness and pain during resistive wrist extension. Medial epicondylitis is characterized by epicondylar tenderness and pain during resistive wrist flexion (Walker-Bone *et al.*, 2004). Epicondylitis is described as a cumulative trauma disorder, which has been found to be a major cause or lost time at work (Armstrong, 1996). Unaccustomed forceful movements, high repetition, awkward postures and insufficient rest can lead to inflammation of the tendon (Gerr *et al.*, 1991). When a person is suffering from medial, or lateral, epicondylitis, they experience a decrease muscle function of the arm, as well as a reduction in grip strength (Pienimaki *et al.*, 2002).

2.3 Strength Testing

Human muscle strength testing has been the subject of much research in the last half century. There are different types of strength testing: Iso-metric, iso-tonic, and iso-kinetic are just a few. The measurement of the muscle strengths of individuals and groups has a very practical purpose. In industries, such as manufacturing or automotive, it is important that jobs are designed in such a way that they can be performed by at least 75% of the female population. Research has shown that if jobs are not designed to be acceptable to at least 75% of the female population, a worker is three times more likely to suffer a low back injury (Snook, 1978). For this reason, manufacturers must take into account the acceptable levels of force production of a worker. In the automotive industry, for example, many studies have been conducted to determine what the acceptable force limits are for certain movements or tasks. These limits are based on research data from studies looking at force production for a large variety of tasks such as repetitive hand impacts, lifting, carrying, and pushing (Fernandez *et al.*, 1991; Potvin *et al.*, 2000; Snook and Ciriello, 1991). In an effort to minimize or reduce musculoskeletal injuries, it is imperative that design engineers, health and safety professionals and ergonomists, among others, are knowledgeable of human strength capabilities. With research strength data, engineers and designers can attempt to accommodate as many people as possible in their designs.

One of the strength related research questions that has been examined extensively is job pre-selection strength testing (Keyserling *et al.*, 1980). It was found that when job simulated strength testing was used as pre-selection criteria, incidents of low back pain decreased to one third of levels where no such protocol was used. This process would attempt to disqualify potential applicants to a job based on their strength capabilities. This process however, is often not available to the company due to legislation about equal rights as well as union opposition. Furthermore, this process goes against some of the current ergonomic thought of fitting jobs to people, not people to jobs (Armstrong *et al.*, 1992). Having said that, pre-employment simulated strength screening has been found to be a valid way of reducing injuries when compared against no screening (Keyserling *et al.*, 1980).

There are two different categories of muscle strength testing: dynamic and static. These tests can be used in many different scenarios, however the general consensus states that, for dynamic tasks, dynamic muscle strength testing should be used. Conversely, for static tasks, static muscle strength testing should be used (Mital and Kumar, 1998b). For the current study, the strength testing will be static as the laboratory tasks in question are static. For the most part, workers performing tasks on an assembly line are largely in static postures and exerting force with minimal movement during the effort. Most of the current literature is the result of isometric strength testing due the relative ease of this method when compared to dynamic strength testing (Kroemer, 1999).

2.3.1 Dynamic Strength Testing

Dynamic muscle strength testing is the form of testing in which both muscle length changes and body segment positions change (Mital and Kumar, 1998a). An example of dynamic muscle testing would be testing the strength of specific muscles over a range of motion such as during a biceps curl or a bench press.

There are a few different types of dynamic strength testing such as iso-tonic and iso-kinetic strength testing. Iso-tonic testing is characterized by a constant joint moment. The problem, however, is that there is a changing of the muscle lever arm across the range of motion causing a change in muscle force. This change in force renders most movements non iso-tonic which ultimately renders this form of testing inappropriate for some industrial applications (Mital and Kumar, 1998a).

The second type of dynamic strength testing mentioned above is iso-kinetic. In this type of testing, the rate of shortening or lengthening is kept constant during a muscular exertion. The key with iso-kinetic testing is constant velocity, or angular displacement about a joint. To simplify, iso-kinetic strength is the measure of a person's maximum voluntary contraction (MVC) when involved body segments move at constant speed (Mital and Kumar, 1998a). Iso-kinetic testing has been used in numerous studies in order to determine muscle strength (Chandler et al., 1992; Ivey et al., 1984; Ivey et al., 1985; Jaric, 2002; Stanley et al., 2004). In addition to the dynamic strength tests described above, there are others such as iso-inertial and psychophysical strength testing, which are more situation specific tests, as well as simulated job dynamic strength and repetitive dynamic strength testing (Habes and Grant, 1997; Resnick and Chaffin, 1995).

2.3.2 Static Strength Testing

Static strength testing measures the capacity for a person to exert a maximal force or torque in a single isometric contraction. In this testing, the joint angle(s) do not change. The measured applied force or torque over time is a result of the internal muscular effort amplified by the mechanical advantage of the body segments involved (Mital and Kumar, 1998a).

There are a few more specific types of static strength testing. Simulated job static strength is similar to dynamic simulated job strength testing, however subjects remain in one of the task postures. Another type of static testing is called continuous static muscle strength testing. The goal of this type of test is to record how the strength declines during a sustained contraction, giving a representation of endurance time. It has been found that, in the first two minutes, there can be a rapid decline in static strength, as much as 75% of the recorded MVC. An exertion of 20% of a subjects maximum however, can be sustained for several minutes (Mital and Channaveeraiah, 1988). Another study examined the effects of effort level on endurance times of shoulder girdle muscles (Garg *et al.*, 2002). When comparing results to that of similar research (Rohmert, 1973), endurance times were overestimated with efforts greater than 45 %MVC and underestimated with efforts less than 45 %MVC. Endurance time was also found to decrease as the shoulder flexion angle increased up to 120°.

Finally, repetitive, static muscle strength testing looks at the maximal exertions applied at given frequencies. Between exertions there is a rest period in which the muscle can recover. This type of testing also results in a decrease in static strength but not as rapidly as in the above type. This type of testing has a psychophysical component to it as well. When subjects perform at their own pace, using non-powered hand tools, the torque has been shown to decline 30% after two minutes and 40% after four minutes (Mital and Channaveeraiah, 1988).

2.3.3 Shoulder strength testing

2.3.3.1 Stobbe (1982)

Stobbe (1982) conducted isometric testing of the arm, shoulder, lower back, abdomen, thigh and leg. For these tests Stobbe had a total of 67 subjects (35 males and 32 females). Stobbe further separated his subjects into two groups based on age (university and not university age). The tests of shoulder strength were conducted in the same torso posture with varying hand, arm and forearm positions. The shoulder axes tested were medial and lateral humeral rotation, horizontal shoulder strength (both forward and backward) shoulder adduction and shoulder abduction. For each of the above mentioned tests, subjects were seated in a chair with three stabilization belts to prevent movement at the hips, shoulders and torso (Figure 7). During the test the subject's legs hung free, however, between tests there was a foot rest subjects could use.

During medial humeral rotation tests, the major muscles active in the exertion were latissimus dorsi, pectoralis major, subscapularis and teres major. The load cell was located above and posterior to the limb being tested (Figure 7) with the elbow flexed to 90° and the arm in the vertical plane. The arm was at a vertical angle of 90° to the torso and horizontal angle of 0° (in line with the shoulders). Schanne (1972) compared humeral rotation strength against joint angles and found a linear relationship that decreases through the range of motion. The test position was chosen due to its close proximity to where Schanne (1972) found subjects capable of exerting their maximum.

Around the arm, proximal to the elbow, was a padded cuff or limb guide to immobilize the arm, preventing additional muscles from aiding in the exertion. Attached to the load cell was a force cuff which was placed around the wrist of the subject. During the force exertions the subject pulled against this cuff to elicit a force. In this study the subject was instructed to pull with their wrist and exert a force to simulate the rotation of their hand forward and downward (Table 2).

During the lateral humeral rotation test, the major muscles active in the exertion were infraspinatus and teres minor. The subject was seated and restrained as stated above. The load cell was located in front of the subject and at the height of their elbow. The elbow was at 90° with the upper arm parallel to the torso with the hand semi-prone. The vertical shoulder angle was approximately 5° (from torso) with a horizontal angle of 0° (in line with shoulders) (Figure 7). The test angle for this exertion was 0° in the horizontal plane (parallel to the torso) which represents where Schanne (1972) found subjects capable of exerting their maximum. Once again the force cuff was just proximal to the wrist and there was a limb guide preventing significant movement of the arm. Subjects were instructed to exert a force away from the body against the force cuff simulating lateral humeral rotation (Table 2).

During the forward horizontal motion tests, the major muscles active in the exertion were the coracobrachialis, deltoideus and pectoralis major. The subject was seated and restrained as stated above. The load cell was located directly behind and at the same height as the subject's shoulder. The elbow angle was 90°, the vertical shoulder angle was 90° in the medio-lateral axis and the horizontal shoulder angle was 0° in the longitudinal axis (Figure 7).

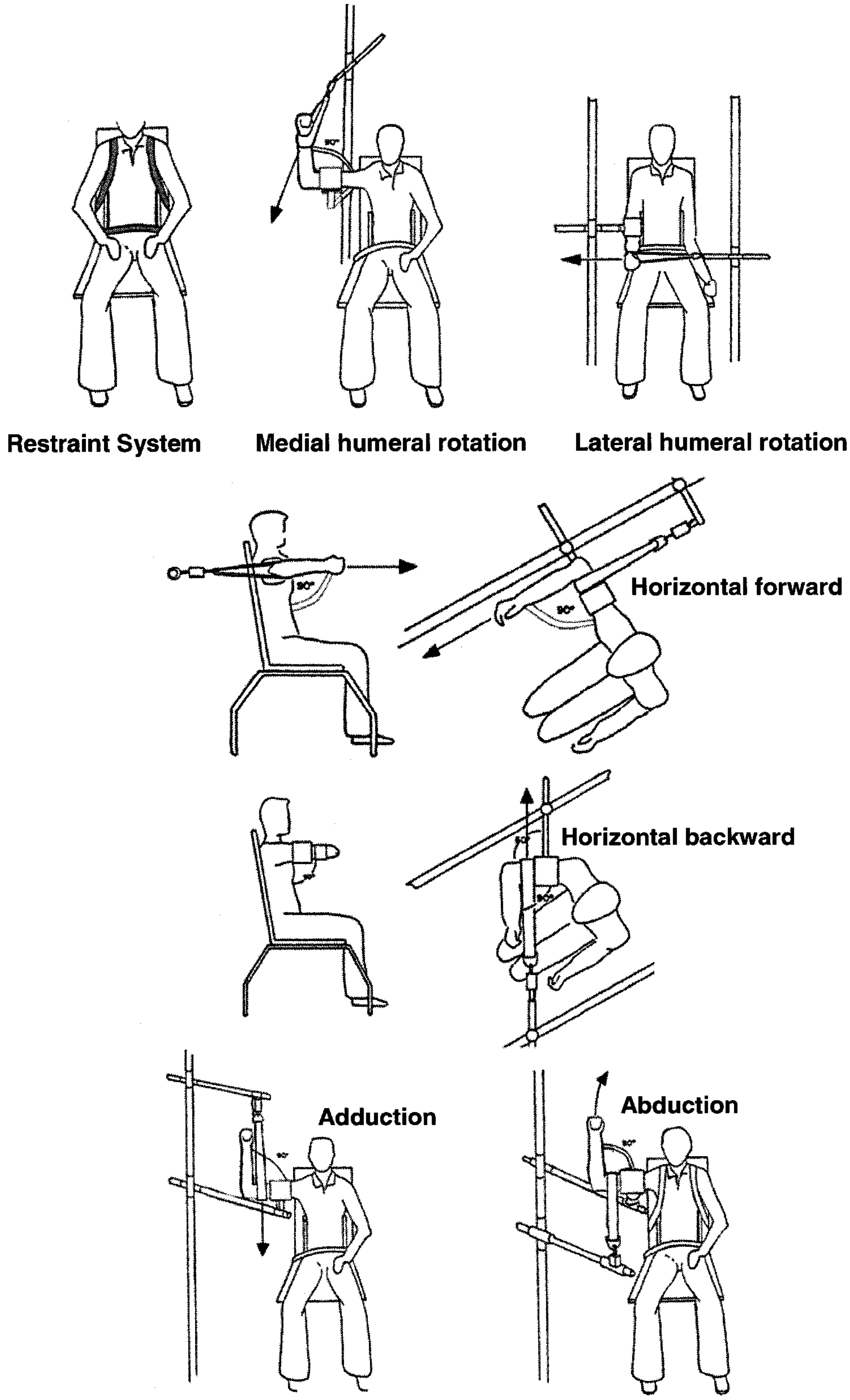

Figure 7: Restraint system and testing apparatus to test all 6 shoulder strength about all three axes. (n=67) Adapted from Stobbe (1982).

The test position for this exertion was based on previous strength studies looking at horizontal shoulder angle conducted by Williams (1959), Clark (1966) and Schanne (1972). The consensus of these researchers seems to be that subjects were strongest with a negative shoulder angle. This is when the elbow is posterior to the plane of the back. Stobbe chose a horizontal angle of 0° (where the elbow is in the frontal plane) due to the ease for subjects to attain this position and for ease of testing. Both the arm and the forearm were horizontal for this test with the hand prone to the floor. The force cuff was located just proximal to the elbow with the limb guide further proximal to that, preventing significant movement. Subjects were instructed to exert a force in the forward direction in the horizontal plane (Table 2).

During the backward horizontal motion tests, the major muscles active in the exertion were the deltoideus, latissimus dorsi, teres major, and trapezius (intermediate transverse fibers). The subject was seated and restrained as stated above. The load cell was located in front of, and at the same vertical height as, the subject's shoulder. In this condition, the load cell was on a pole on the opposite side of the subject's body from the testing arm. The elbow angle was 90°, the vertical shoulder angle was 90° (in the medio-lateral axis) and the horizontal shoulder angle was 60° in the transverse plane relative to the frontal plane (Figure 7). The test position for this exertion was based on previous strength studies looking at horizontal shoulder angle conducted by Williams and Stutzman (1959), Clark (1966) and Schanne (1972). The data from these researchers suggest that maximum strength occurs between a shoulder angle of 45° and 100° in the transverse plane. A test angle of 60° with the medio-lateral-axis was used because it is near the center of the maximum range and is not near the range of motion extremes. Both the arm and the forearm were horizontal for this test with the hand semi-prone. The force cuff was located just proximal to the elbow with the limb guide further proximal to that preventing significant movement and adding support between trials. Subjects were instructed to exert a force in the rearward direction in the horizontal plane (Table 2).

The fifth test at the shoulder was shoulder adduction. During shoulder adduction test the major muscles active in the exertion were the coracobrachialis, infraspinatus, latissimus dorsi, pectoralis major, subclavius, teres major and minor. The subject was seated and restrained as stated above. The load cell was vertical and located directly above the arm lateral to the head. The pole is located slightly posterior to the subject. The elbow angle was 90°, the arm is horizontal in the frontal plane and at 90° in the vertical direction (in line with shoulders). The forearm is perpendicular to the floor and the hand is supine relative the head (Figure 7). The test position for this exertion was based on previous strength studies looking at horizontal shoulder angle conducted by Clark (1966) and Schanne (1972). The data from these researchers do not agree on the vertical shoulder angle in which the subjects can exert the greatest force. While one curve is essentially flat, the other plateaus between 90° and 120°. For this reason, and for the ease of administering this test, Stobbe selected a vertical angle of 90° (to the torso). The force cuff was located just proximal to the elbow with the limb guide further proximal to that preventing significant movement and adding support between trials. Subjects were instructed to exert a force downward in the vertical plane. Test data is represented in Table 2.

During shoulder abduction tests, the major muscles active in the exertion were the deltoideus, infraspinatus, supraspinatus, and serratus anterior. The subject was seated and restrained as stated above. The load cell was vertical and located directly beneath the arm. The pole is located slightly posterior to the subject. The elbow angle was 90°, the arm was horizontal in the frontal plane and at 90° in the vertical direction (in line with the shoulders). The forearm was perpendicular to the floor and the hand is supine relative the head (Figure 7). The test position for this exertion was based on previous strength studies looking at horizontal shoulder angle conducted by Elkins *et al.*(1951), Clark (1966) and Schanne (1972). The data from these researchers seems to agree that there is a plateau in strength when the vertical shoulder angle is below 110°, after which there is a slight decrease. For this reason, and for the ease of administering this test, Stobbe selected a vertical angle of 90° (in line with the shoulders). The force cuff was located just proximal to the elbow with the limb guide further proximal to that preventing significant movement and adding support between trials. Subjects were instructed to exert a force upward in the vertical plane (Table 2). Stobbe's testing resulted in a strength database for males and females. For example, it was found that for medial humeral rotation the 50th percentile female was capable of exerting 21.3±8.0 N·m. Shoulder adduction data showed that the 50th percentile female was capable of exerting 32.8±13.0 N·m.

Table 2: Summary of female shoulder moments for 6 different test positions in N·m. (n=67) Adapted from Stobbe (1982).

	Min	Mean	Max	SD	percentile 5%	percentile 50%	percentile 95%
Medial Humeral Rotation	8.0	21.4	44.3	8	8.3	21.3	39.1
Lateral Humeral Rotation	12.0	19.9	32.5	5	12.7	18.6	32.3
Shoulder Horizontal Forward	10.5	39.1	67.4	13	13.0	38.9	63.2
Shoulder Horizontal Backward	18.6	34.1	57.6	11	19.6	33.3	54.0
Shoulder Adduction	11.0	34.9	68.8	13	12.4	32.8	59.5
Shoulder Abduction	13.3	36.9	57.8	10	18.4	36.9	56.0

The data that Stobbe (1982) collected was some of the most complete data compiled to date. With this data he was able to assemble a database of strength values for six motions at the shoulder. His study however, while thorough, did not explore many potential postures or potential hand locations to determine strength in these different positions. There were only four hand positions tested in Stobbe's thesis (1982). For the hand positions tested, further information could have been obtained by testing strength in all six directions: up, down, exert right, exert left, push and pull. A more comprehensive database of strength values is needed to accurately predict strength.

All of the testing positions that Stobbe (1982) used were decided upon using data from other studies. Previous research was examined and used to determine at what shoulder angles maximal strength values would be recorded. What Stobbe was looking for was the maximum amount of force that a subject could produce at some point within the range of motion for each action. In the current manufacturing industry, parts, job tasks, and work stations are designed by engineers and designers. These people need to know what the human capabilities are at certain locations in 3-dimensional space. Although valuable, the Stobbe data are not currently capable of providing all the necessary answers to designers or ergonomists.

While a range of data was provided for shoulder strength, there are a number of reasons why Stobbe's values have limited applications for predicting the hand force capabilities often needed in industry. In his study, Stobbe did not record force production at the hand. The recordings were from the forearm just proximal to the wrist (two tests) and from the arm just proximal to the elbow (four tests). This may cause some additional discrepancies when determining acceptable hand forces. By recording the force from the arm, there is no accounting for possible errors about the elbow and possible errors at the wrist, as well as shoulder strength contributions in multiple axes.

Another issue of note is the restraint system which Stobbe (1982) used. In actual manufacturing tasks, employees are not always restrained. While subjects may be physically restrained by guard rails, and physical barriers, they are not restrained to which body parts can contribute to the effort. Stobbe wanted to know what specific strengths were for specific movements. In order to accomplish this, there had to be a level of control. Stobbe restrained his subject's movement in order to control which muscles and muscle groups they used to perform the tasks. This, however, may not translate accurately into actual work tasks performed in the manufacturing industry. Force applied in the manufacturing industry is almost always applied at the hands, seldom is it applied by another part of the body. Work tasks do not always require certain or specific arm orientation as they did in this study.

2.3.3.2 Other strength studies

Haslegrave, Tracey and Corlett (1997) looked at strength capability in various awkward working postures. Prior to this study, only one other study was found that looked at strength in awkward postures (Warwick et al., 1980). Strength data were taken from subjects in four different main trunk postures and 10 different arm postures. For each tested condition, subjects exerted a force about three axes and in six directions. The testing postures are described in Table 3. There were two groups of 12 males subjects, one group for standing tasks and one group for lying supine tasks. All subjects were between the ages of 20-35 years. The subjects selected were a representative sample of the British male population.

Table 3: Postures tested indicating location and torso orientation during the exertion about three axes and six directions. (n=24) Adapted from Haslegrave et al. (1997).

Task	Location of the point at which the force was exerted
Standing, facing forward (standing condition)	**0°** rotation, height at subject's shoulder level, right foot at maximum reach distance
Standing, twisted sideways	**90°** of rotation, height 142 cm (approximately shoulder level), distance right foot to test handle = 45.7 cm **135°** rotation to right, height 142 cm (approximately shoulder level, distance right foot to test handle =53.9 cm
Standing, working overhead	Test handle mounted at 4 locations above the right foot position, the locations calculated to be at maximum reach distance from the subject's right shoulder - at angles of 15° forward, 15° rearword, and 15° to each side

Haslegrave *et al.* (1997) identified a potential confounding variable with strength testing in their study. Their question was, "Is it appropriate to test subjects in absolute space?" Given the fact that everyone is of different anthropometry it was decided to use the subject's size as determinants of testing positions. Subjects were placed in one of three categories, short (<30^{th} percentile), average (30^{th} – 70^{th} percentile) and tall (> 70^{th} percentile). Each category had predefined locations and postures for strength testing. The only undefined posture or location were ones in which the subject's maximum reach was used.

In addition to setting anthropometric-based testing locations, Haslegrave *et al.* (1997) did not restrain their subjects. Only in the tasks in which the subjects were lying supine were they able to exert an opposing force. In this case, they were able to use the floor to push against, potentially increasing the amount of force they were capable of producing. Additionally, there were no sitting conditions in the experiment. During the testing conditions subjects were allowed to adopt whatever posture they felt would result in the highest strength. Exact positions, however, were still important to the reliability of the research and were determined in this case by specification of the 3D location of either the ball of the dominant foot or the acromion of the dominant shoulder.

Prior to the beginning of testing, subjects provided a baseline strength measurement by exerting a maximum pushing force at shoulder level while standing at maximum reach distance. The reasoning behind this location was three fold: 1) this posture is common to numerous other strength testing research studies, 2) the ability to use body weight to increase the exerted force or contribute to the muscle exertion is limited, 3) this provides a common baseline measurement across all subjects for inter-subject comparison.

It was found that in the control condition, standing with force application in the sagittal shoulder plane, and at shoulder height, the mean push force was found to be 277±106 N (Table 4). In twisted postures, reach distance was shown to have the greatest effect of lifting force. As the distance decreased, lifting force increased. Furthermore, exertions in the vertical plane were greater than those in the horizontal direction. When working overhead or lying supine, it was found that as the reach distance was decreased, the force exertion decreased.

Table 4: Force (N) exerted by subjects in 7 locations and three axes at a maximum reach distance. Values were then used to determine how strength is influenced by task layout. (n=24) Adapted from Haslegrave et al. (1997).

	Horizontal		Horizontal		Vertical	
Location	Push	Pull	Across Body	To Side	Lift	Press
Standing						
Directly forward, shoulder height						
Mean	277					
SD	106					
Twisting 90° sideways, height 142 cm, horizontal distance 45.7 cm						
Mean	292	206	228	159	303	323
SD	119	65	134	68	159	134
Twisting 135° to rear, height 142 cm, horizontal distance 53.9 cm						
Mean	284	197	199	157	271	323
SD	110	52	100	65	124	134
Standing working overhead						
15° forward						
Mean	137	132	119	128	507	458
SD	46	42	52	54	216	101
15° rearward						
Mean	101	95	115	125	424	432
SD	30	42	35	44	107	172
15° to left						
Mean	124	130	131	128	478	442
SD	37	30	40	50	227	117
15° to right						
Mean	125	123	127	136	473	458
SD	25	33	38	50	195	127

This study appears to have been conducted with the real workplace application in mind. This helps in the translation of results for real world application and design. The lack of positional and physical restraints allowed subjects to perform the task in the way they felt most comfortable. While the mandatory location of the foot is not always translatable to the workplace, it is a method of control that is important. In this study, there was a variety of postures tested, and all locations were tested in six directions. What was lacking, however, was sizeable horizontal and vertical deviation. For example, the overhead exertions only varied 15° on either side of being directly overhead (considered to be 0°). The same can be seen for forward and backward exertions. The results of these tests depict little variability between these locations in force output (Table

4). Additional strength data are required to aid in the extrapolation of intermediate values which were not covered in this study.

Shoulder strength was also measured in another study looking at volitional torque capabilities for male and female subjects with different tools (Mital and Sanghavi, 1986). There were 55 subjects recruited for this study, 30 male and 25 female. There were five independent variables tested: 1) tools (n=5, two screwdrivers, spanner wrench, vise grip and socket wrench), 2) heights of torque application (n=3, eye, shoulder, and elbow height), 3) worker postures (n=2, sitting and standing), 4) reach distance (n=6, 45.7, 58.4 and 71.1 cm from seat reference to point for the sitting posture; 33, 45.7 and 58.4 cm from the ankles for the standing posture), and 5) tool orientation (n=6, given by the angle of the longitudinal axis of the arm with respect to the mid-sagittal plane). It was found that, on average, females exerted 66% of the torques exerted by males. The mean torque exerted by females was 124.4 kg-cm. When comparing the two postures, it was found that standing resulted in higher torques (178 kg-cm vs. 142 kg-cm in sitting) with the highest occurring at the smallest reach (189 kg-cm) and then showing a decrease as the distance increased. This study looked at different hand positions in various postures including various reaches and arm angles. What was not tested however, were different actions. All conditions tested torque generating capabilities at the hand, with no arm abduction, adduction or lift and lower tasks. Much more data could be collected using their methodology and locations to increase the strength database.

Another study looked at the reliability of isometric strength testing of the trunk, hands, and shoulders (Essendrop *et al.*, 2001). Nineteen subjects participated in this study (6 males and 13 females). The subjects performed five different isometric strength tests, including scapular elevation and shoulder abduction strength. Subjects performed the test twice, with the second trial seven days later at the same time of the day. MVC's were taken of each subject and for each strength measure. In this study, the subject was instructed to ramp up the force over a five second period and then maintain it for two seconds, followed by a ramp down.

Essendrop *et al.* (2001) measured shoulder elevation strength with the subject seated in a chair and their feet dangling. The shoulders were elevated against the resistance of two dynamometers (one on each side) affixed to the wall, with the subject looking straight ahead. The elevation force was found to be 586±203.6 N. Shoulder abduction was measured with the elbows flexed at 90° with the subject seated in the same chair as mentioned above. The subject was asked to exert a force outward with both arms against two dynamometers placed just proximal to the lateral epicondyls of the humeri. The abduction strength was found to be 195±87.0 N. Strength test methods recorded from this study were similar to those of Stobbe (1982). They were tested, not from the hand but from the shoulders and from just proximal to the elbows. These values are therefore not capable of accurately predicting exertion forces at the hands.

Comparison studies between standing and seated shoulder strength have also been conducted. In a recent study, isometric strengths of people who were in the working population were collected in both sitting and standing postures (Das and Wang, 2004). Researches enlisted 16 university aged participants (8 male and 8 female). The apparatus used (Figure 8), including a table and chair, was completely adjustable in order to accommodate all subjects regardless of anthropometric differences.

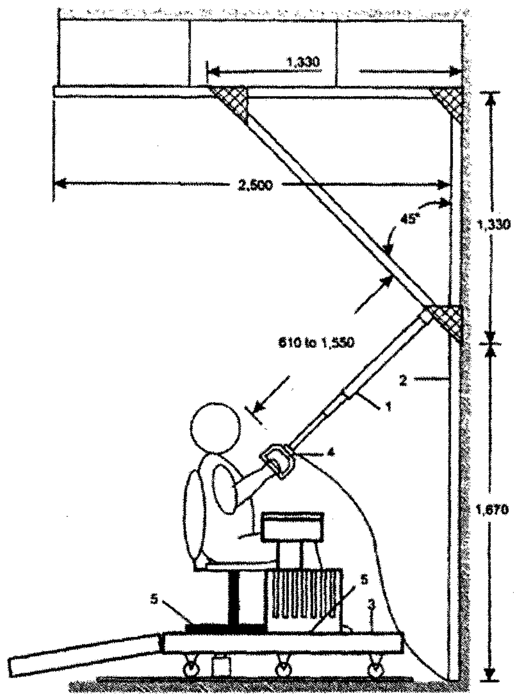

Figure 8: A computerized isometric strength measurement system. 1. extendable arm, 2. supporting track, 3. platform, 4. force transducer, 5. stability sensor. Adapted from Das and Wang (2004).

In addition to testing males and females in both standing and seated postures, various sub-postures were tested as well. There were 3 reach distances (normal, maximum and extreme), 3 vertical angles (0°, 45° and 90° relative to elbow height), 4 levels of horizontal angle (0°, 45°, 90°, and 135° on the right side of the frontal plane), and 2 force directions (push and pull). In each posture, the subject was asked to exert a force in a 3D location relative to their limb length. The forces were to be ramped up as fast as possible and held for five seconds. Subjects were not allowed to lean or grab onto any objects during their force exertions but were free to assume any position. A selection of postures with results are listed in Table 5 and Table 6 (Das and Wang, 2004).

Table 5: Female pull strength (N), seated and standing with subject using a maximal reach. Adapted from Das and Wang (2004).

Shoulder Angle		Standing		Seated	
Vertical Angle	Horizontal Angle	M	SD	M	SD
0	45	79.05	22.97	119.28	52.38
0	90	65.34	23.31	115.50	62.72
45	45	100.96	33.03	125.26	56.02
45	90	90.76	25.91	119.71	55.27

Table 6: Female overall average push and pull strengths (N). Adapted from Das and Wang (2004).

	Standing	Seated
pull	85.09	120.50
push	84.50	66.60

The purpose of the above study was to determine the difference in strength capability between seated and standing postures. Female standing pull strength was found to be lower at extreme reach in the horizontal plane than in other locations. Female seated pull strength was found to be the highest at extreme reach and at 45° in the vertical angle. Overall, it was found that the strength in the standing position was 79% of that in the seated position.

One limitation of the Das and Wang (2004) study is the low sample size. When building a strength database, sample size and subject pool should be very important. Further to that, the subjects ranged in age from 20 – 39 years, which is not a representative sample of the working population. The study did, however, look at a number of different positions in two different main postures. On the other hand, only push and pull forces were recorded for this study. No upward, downward, exert right or left forces were measured.

2.3.4 EMG Studies

There have been additional studies conducted that look at the EMG level in the muscles during upper extremity exertions. In a study looking at overhead work, eight combinations of both vertical and horizontal distance were studied. Twenty subjects participated in this study (12 males, 8 females) with a mean age of 31±8.1 yrs (Anton *et al.*, 2001). In this study, the subjects stood on a step ladder at either the low or the high step and exerted an upward force simulating a drilling task. All simulated drilling tasks were performed in the sagittal plane. These tasks were in three different reaches; close, medium and far.

The results of the study by Anton *et al.* (Anton *et al.*, 2001) indicate that increasing the reach of drilling increases the muscle activation. The results of this study, however, apply to the horizontal distance, not the vertical height. There was a greater increase in the muscle activation levels at the high step when compared to the low step. It would appear that it is more advantageous to perform work close to the body when working overhead. This help lessened the muscle fatigue, which is found to correspond to a decrease in strength production.

In the study by Anton *et al.* (2001) further strength data were recorded. The conclusions support those found in other previous studies (Arborelius *et al.*, 1986; Haslegrave *et al.*, 1997). This study however, did not take into account locations outside of the sagittal plane. Furthermore, no isometric exertions were conducted in any other direction other than upward. While the information is valuable, upwards is not the only direction in which forces might have to be applied in industry. In addition, as the arm is abducted and moved farther laterally, different fibers and muscles are involved in the exertion. There may be very different values recorded for exertions further away from the midline for example.

2.3.5 Elbow

Research measuring elbow strength is not as common as shoulder strength measurements. Stobbe (1982) conducted isometric testing of the arm, shoulder, lower back, abdomen, thight and leg. For these tests, they had a total of 67 subjects (35 males and 32 females). Stobbe (1982) further separated his subjects into two groups, based on age (university students, other). The tests of elbow strength in flexion and extension were conducted in similar postures. For each of the tests, subjects were seated in a chair with three stabilization belts to prevent movement from parts of the body not being tested as per the shoulder tests.

During the elbow flexion test, the major muscles active in the exertion were biceps brachii, brachialis, and brachioradialis. The load cell was located above the upper horizontal support of the chair just below the chair seat (Figure 9) with the elbow angle at 90° and the forearm horizontal and the hand semi-prone. The arm was at a vertical angle of 0° (at side) and horizontal angle of 0° (at side). The test angle used was based on previous research finding the greatest elbow strengths between 70° and 100° (Clark, 1966; Elkins et al., 1951; Schanne, 1972; Singh and Karpovich, 1968; Williams and Stutzman, 1959). The elbow angle of 90° was chosen because it was easy and three of the five researchers recorded maximum strength at this angle. Around the arm, just proximal to the elbow, a padded cuff or limb guide was used to immobilize the arm, preventing additional muscles from aiding in the exertion. Attached to the load cell was a force cuff which was placed around the wrist of the subject. During the exertions, the subject pulled against this cuff to simulate the flexion of their hand upward (Table 7).

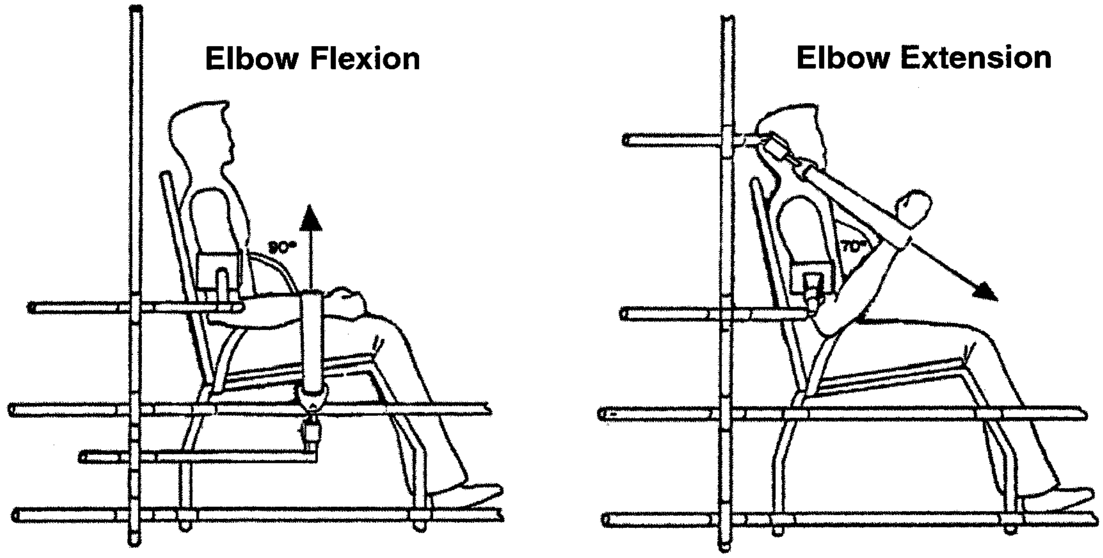

Figure 9: Elbow flexion and extension in restraint apparatus. (n=67) Adapted from Stobbe (1982).

During the elbow extension test, the major muscles active in the exertion were anconeus and triceps brachii. The load cell was located directly above the subject's shoulder with the elbow angle at 70° and the hand semi-prone. The arm was at a vertical angle of 0° (at side) and horizontal angle of 0°(at side)(Figure 9). The test angle used was based on previous research that found the greatest elbow extension moments consistently between 70° and 100° (Clark, 1966; Elkins et al., 1951; Schanne, 1972; Singh and Karpovich, 1968) with an elbow angle of 70° generally having the highest strength. Around the arm, just proximal to the elbow, was a padded cuff or limb guide to immobilize the arm, preventing additional muscles from aiding in the exertion. Attached to the load cell was a force cuff which was placed around the wrist of the subject. During the exertions, the subject pushed against this cuff to elicit a force (Table 7).

Table 7: Summary of female elbow moments in 2 test positions. N·m (n=67) Adapted from Stobbe (1982).

					percentile		
	Min	Mean	Max	SD	5%	50%	95%
Elbow Flexion	15.7	40.8	59.9	11	18.9	40.3	57.1
Elbow Extension	8.2	25.6	39.0	8	11.1	25.2	38.3

Another study conducted by Keyserling *et al.* (1980) looked at what they termed arm lift strength There were 54 males and 27 females in this study, with a mean age of 32.7±5.9 yrs. One of the four strengths tested was an arm lift where the subject stood fully upright with arms at their sides and the elbows flexed at 90°. The subjects were instructed to perform a sustained five second voluntary isometric exertion in this position. It was found that the mean female arm lift strength was 223.2 N±61.9 N. This study did not, however, look at any other strength testing for the elbow (or arm) at all and arm extension was not tested. While subject size was adequate, no other positions were tested other than those noted.

Mogensen and Stobbe (1985) conducted a study looking at testing the arm strength at the elbow. In this study, there were twenty student subjects (ten males and ten females) with ages between 18 and 33 years. The subjects stood in front of an apparatus with two handles that could be adjusted to place the elbows at 90°. With arms at their side, subjects exerted a force upward once for a period of five seconds and a second time for a period of three seconds. It was found that, for a mixed gender group, the mean forces were 358 N and 376.9 N for the five and three second contractions, respectively. As with the previously mentioned study, only one posture and direction was tested for this experiment. No lateral or vertical displacement of the force transducer was employed to determine the relationship between subject strength and posture or hand position. In addition, the subject size of 20 was rather small.

Push and pull strength at the elbow has also been studied in different postures. Das and Wang (2004) compared these two strengths in a standing posture and a seated posture. A description of this study can be found in the preceding text. Overall, the average for female push and pull values demonstrated that higher force could be exerted in a pull direction when seated. The opposite was found for pushing. The strength values for select postures are listed in Table 8 for subjects at a normal reach.

Table 8: Female pull strength (N), seated and standing with subject using a normal reach. (n=8) Adapted from Das and Wang (2004).

Shoulder Angle		Standing		Seated	
Verticle Angle	Horizontal Angle	M	SD	M	SD
0	45	74.47	27.18	101.04	45.30
0	90	66.20	24.02	106.84	52.53
45	45	89.42	37.89	115.76	58.55
45	90	90.35	31.71	113.54	56.89

2.4 *Job pre-selection strength testing*

Job pre-selection or placement is another area that has been researched related to strength testing. The relationship between pre-hire strength testing and post hire medical incidents has been the subject of much debate. In one study, four postures that were consistent with task requirements at the company were used to test the strength of applicants (Keyserling *et al.*, 1980). There were 54 males and 27 females in this study, with a mean age of 32.7± 5.9 years. There were 20 jobs selected in this plant that were known to have high strength demands. Each selected job was then broken down into it's smallest parts and the force required to complete the task was recorded. The tasks were tested for strength requirements during the following tasks: 1) an arm lift (elbow flexed at 90°), 2) a back lift, 3) a push out (hands at slightly higher than elbow height and leaning slightly forward), and 4) pull in (hands at shoulder height, leaning slightly rearward). Once these demands were identified, criteria were developed for passing the test.

The subjects of this study were then split into a control and experimental group. Subjects in the experimental group had to exceed the minimum strength demands criteria for the jobs in order to be hired. Each subject performed a five second voluntary isometric exertion. Of the four postures described by Keyserling *et al.* (1980), two had a shoulder strength component. The first was a push out exertion from a standing posture leaning forward. For tested females, the mean force was 235.2±73.9 N. The second test was a pull-in exertion from a standing posture leaning backwards. For tested females, the mean force was 336.8±95.8 N. It was found that the medical visit incidence rate, for the control group, was three times that of the experimental group. This study appears to show that human strength can be used as a predictor of risk or injury when the demand is known. Furthermore, it was found that an employee strength-based selection program can be used to reduce injuries.

One of the limitations of the study conducted by Keyserling *et al.* (1980) was the limited strength testing protocol. Only four strengths were tested: push, pull, arm lift and back lift. These four strengths do not account for a large number of tasks that have a large variety of components. A further limitation of this study was that, during the observation period, some of the participants were assigned to other jobs that were not part of this study. No data of medical visits or time on these other jobs was included in this study leading one to question what potential impact the other jobs had on medical visits for the observed jobs. The medical monitoring for this study was conducted for a full year. While a one year observation period can account for acute injuries, it likely does not have the ability to account for longer term or cumulative injuries.

2.5 *Strength and Age*

There is a large amount of existing research regarding strength changes related to age (Chaffin et al., 1999; Chaunchaiyakul et al., 2004; Deschenes, 2004; Hung et al., 2004; Metter et al., 1997; Peebles and Norris, 2003; Runge et al., 2004; Savinainen et al., 2004; Shechtman et al., 2004). According to Chaffin et al. (1999), the strength of the average person is greatest in the late 20's and early 30's. This strength, on average, is 5% less by age 40 and 20% less by age 60. In general, most research demonstrates a decrease in average muscular strength as age increases. This phenomenon can be seen in Figures 10 and 11.

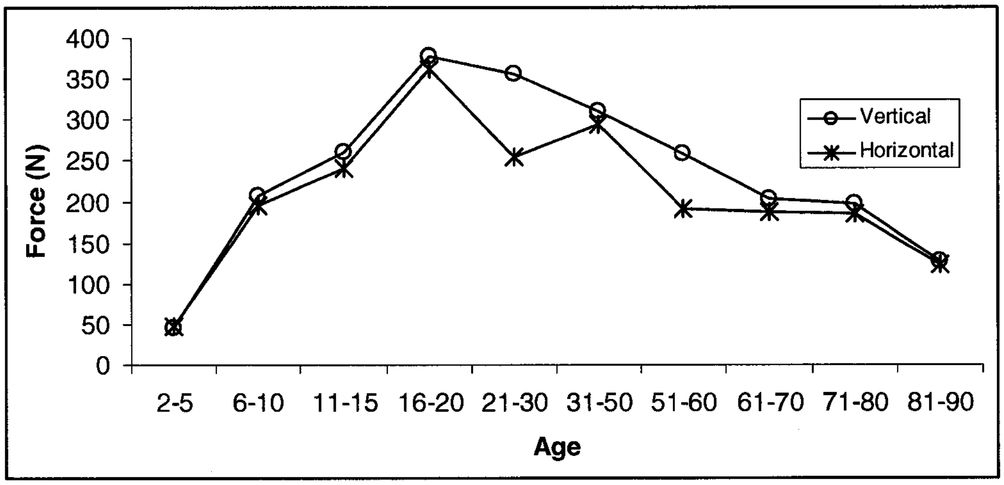

Figure 10: Pull strength (N) - one handed. Adapted from Peebles & Norris (2003)

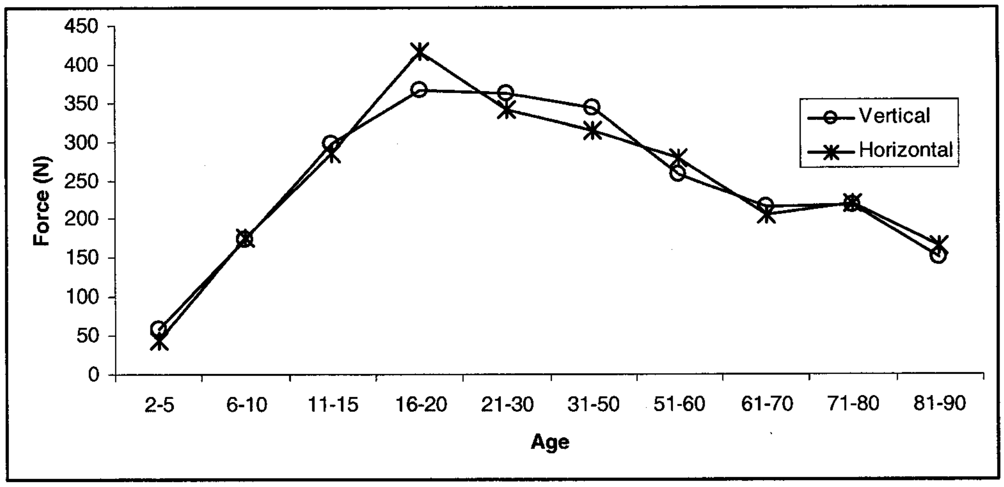

Figure 11: Pull strength (N) - one handed. Adapted from Peebles & Norris (2003).

Chapter 3: METHODS

3.1 Subjects

This study consisted of 29 female subjects in three age ranges: 1) 20-29 years (10 subjects), 2) 30-39 years (10 subjects) and 3) 40-55 years (9 subjects). All subjects were asked if they had any previous upper extremity disorders (Appendix B). Subjects were volunteers and not required to have any prior industrial work experience. The age, height, and mass recorded, of subjects was also be recorded in addition to contact information (Appendix B).

Prior to the commencement of the study, all subjects were asked to both read and sign a written consent form (Appendix A). The University of Windsor's Research Ethics Board reviewed the details of this study and approved of all portions of it.

3.2 Study Design

The current study used biomechanics to establish maximal force limits for hand exertions in various locations. Subjects were asked to exert a maximal voluntary force with their dominant hand, in 20 hand positions and six directions which are similar to those found in the workplace. Force exertions by subjects was performed on an apparatus within a laboratory setting allowing for numerous locations and hand positions. Participants stood in front of the apparatus at a perpendicular distance defined by the researcher using a telescoping post placed on their manubrium. Subjects were then asked to apply maximal voluntary contractions (MVCs) on a handle attached to a triaxial force transducer that was set in various positions. Participants applied MVCs in the direction indicated by the experimenter. Each participant repeated this for a total of six different directions for each position (up, down, left, right, push and pull). Each effort lasted for 3-5 seconds. Subjects performed two trials within approximately one minute for each hand position, resting their hand at their side between each trial. They were given 3-5 minutes rest between hand positions. Subjects were tested in 10 hand positions in each session, returning once, for a total of 2 sessions (total of 20 hand positions). One criterion hand position was determined and subjects performed MVCs in this posture in both sessions. During the force exertions, subjects were given instructions but were not further motivated by the researcher. The aim was to ensure that all force applications were in the direction they are intended. If less than 90% of the resultant force exertion was not in the intended axis, the trial was discarded and recollected. In addition, a bias was collected from each subject, at all three heights and in both reach distances, with their hand on the handle. This bias represents the force at the hand required to support the arm.

The independent variables in this study were the location of the exertion, direction of the exertion and age. As previously stated, there were 20 different hand positions locations relative to the manubrium. These locations were in four planes of motion intersecting the right shoulder at angles in the transverse plane (Figure 12).

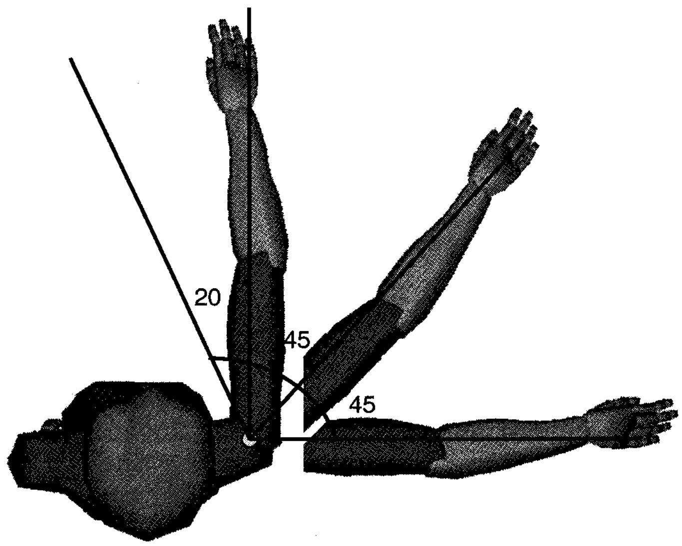

Figure 12: Four angles in the transverse plane with respect to the sagittal plane through the shoulder (0 degrees).

The first plane was through the shoulder but in line with the midline at approximately -20° to the sagittal plane. The second plane was a para-sagittal plane through the right acromioclavicular joint at 0°. The third, at 45° of horizontal flexion in relation to the para-sagittal plane. The final plane was in the frontal plane or at 90° to the sagittal plane. In each hand position subjects exerted a force in six different directions. The forces were push up, push down, push forward, pull backward, exert left and exert right. In all planes except the midline (-20° to sagittal shoulder plane) these positions were also at three heights, 1) head height, 2) shoulder height, and 3) at waist height. In addition, there were two reach distances for each angle and height; 1) 80% of maximum reach, and 2) 40% of maximum reach. Reach distances were chosen to represent the distances near the two ends of the normal working envelope. The testing heights were randomized as well as the testing postures randomized within heights for each subject. After exerting the force, the subjects observed both the amplitude and direction of the force on a computer monitor. For the hand position at the midline, at -20°, only two positions were tested (high and low), at shoulder height at 80% maximum reach distance.

3.1 Instrumentation

3.1.1 Force Transducer

All force exertions were captured and recorded using a 500 lbs. triaxial load cell (500 lb XYZ Sensor, Sensor Development Inc., Lake Orion, MI)(Figure 13). Force data were sampled at 1000 Hz.

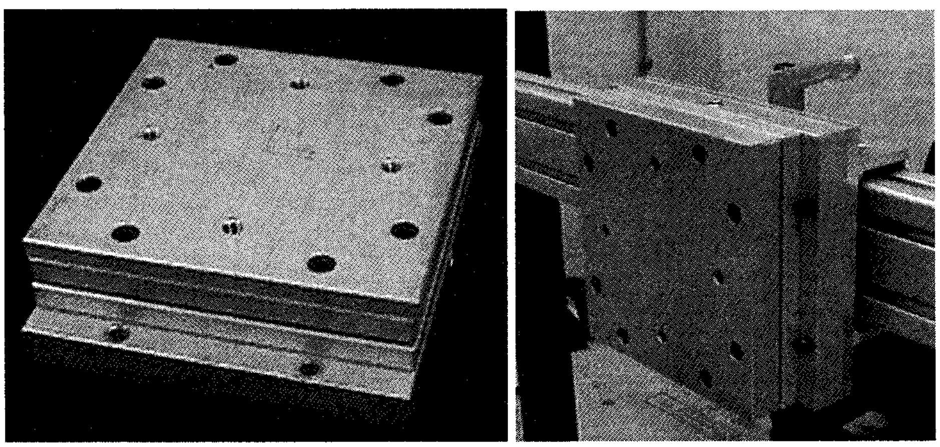

Figure 13: Triaxial force transducer. 152.4mm x 177.8mm x 53.975mm.

Mounted to the load cell was a handle for subjects to grasp. The handle was made of shaped plastic (3/4" diameter), with rounded corners, and padded. This assembly was mounted on a horizontal length of slotted rail (80/20 Inc., Columbia City, IN) (Figure 14). The force transducer was mounted on the rail with linear bearings fitted with a quick release ratchet brake, enabling the researcher to set the location in the horizontal position or *x-axis*. This horizontal tubing was mounted on two vertical lengths 80/20 slotted rails using a linear bearing system fitted with quick release ratchet brake. This assembly allowed the researcher to set the location of the force transducer in the vertical position or *y-axis*. The distance in the *z-axis* was attained by having the subject place their manubrium against a padded telescoping pole, extending from the apparatus.

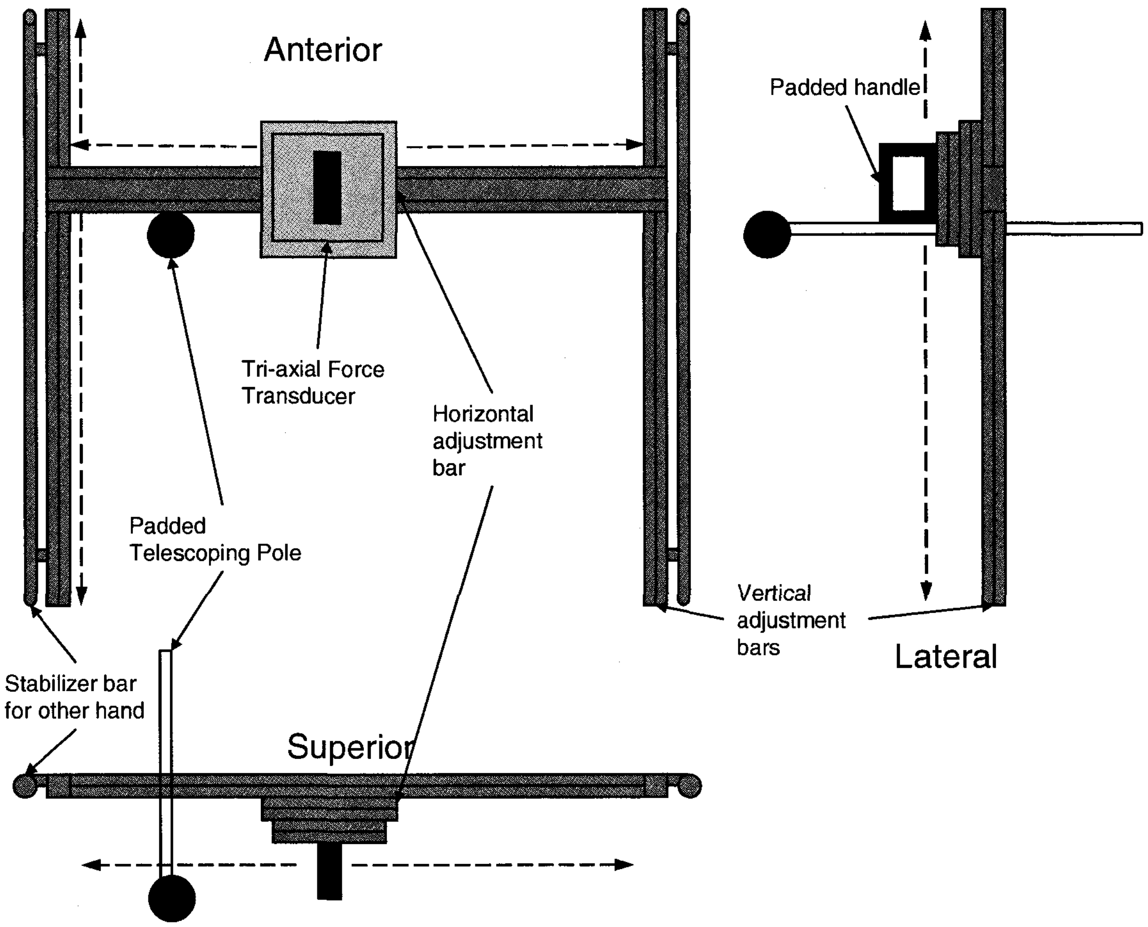

Figure 14: Adjustable testing apparatus housing the force transducer and handle. Viewed from three angles: anterior, superior, and lateral.

3.1.2 Electromyography

For 18 of the subjects, five channels of bipolar disposable surface electrodes were used to predict the muscle force contribution. These were expressed as a percentage of their respective MVC's during each force exertion in all experimental conditions. Ag-AgCl surface electrodes (Medi-trace disposable electrodes, The Ludlow Company, Chicopee, MA) were placed in parallel with each muscle belly along the line of action. Two channels were dedicated to arm musculature. The first channel was on the biceps brachii

(BB) representing arm and forearm flexion. The second channel was on the triceps brachii (TB) representing arm and forearm extension. The remaining three channels, three, four, and five were on muscles acting on or about the shoulder girdle. The third channel was located on the lateral deltoid (DL) representing abduction of the humerus. The fourth channel was located on the anterior deltoid (DA) representing shoulder flexion. The fifth channel was located on the upper trapezius fibers (TR), representing the elevation of the clavicle and the adduction of the scapula and humerus.

3.2 Experimental Protocol

At the start of each testing session the subjects were given a verbal explanation of the purpose and instrumentation of the study. Subjects had the opportunity to ask questions of the researcher prior to the initiation of the study. At this point subject information was obtained, such as, age, mass, height, and hand dominance.

Secondly, for the 18 subjects participating in the EMG trials, bipolar Ag-AgCl sEMG electrodes were placed on the BB, TB, DL, DA and TR. Placement of electrodes was as follows: BB, on the muscle belly, approximately 70% of the way from the proximal aspect of the muscle on the anterior surface, TB, on the long head muscle belly, approximately 30% of the way from the proximal aspect of the muscle on the posterior surface, DL, on the muscle belly, inferior and lateral to the acromio-clavicular joint on the same level with the auxiliary aspect of the arm (Saitou *et al.*, 2000), DA, on the muscle belly directly superior to the auxiliary aspect of the arm, inferior to the acromioclavicular joint, and TR, on the muscle belly approximately 40% of the way from C7 on a line with the acromion (Shiraishi *et al.*, 1995). In addition to the above listed locations, a ground electrode was placed on either the medial or lateral epicondyle of the humerus. Prior to electrode placement, all areas were cleaned with an alcohol solution to ensure optimal contact with the skin.

3.2.1 Testing sessions

Subjects were required to complete 2 testing sessions of approximately one hour in length each. Over the two testing sessions, subjects exerted forces in six directions with a total of 20 different hand positions as described above in section 3.1. The presentation of hand positions was randomized within testing heights as was the presentation of the six force directions within each hand position.

Prior to the initiation of each testing session, MVC's were collected from all five muscles. For each MVC, the experimenter provided resistance throughout the range of motion to ensure the maximum contraction occurs. For the BB, the forearm was flexed at 130° to the arm with the arm at the subject's side. The subject was instructed to pull up as hard as possible while the experimenter applied resistive force in the downward direction at the hand and wrist. For the TB, the subject started with the forearm flexed at 20° and exerted a force downward against the researcher's resistance. For the DL, the subject stood with arm at their side and forearm fully extended. They were instructed to push outward (abduct) while the researcher provided resistance at the wrist. For the DA, the subject stood with arm at side and forearm fully extended. The subject was instructed to flex the arm at the shoulder (rotate arm forward and outward at approximately 35°-45° at the shoulder) while the researcher applied resistance at the wrist. For the TR, the subject stood with arms parallel to the torso, or in the frontal plane while strapped onto a platform with the straps restraining each shoulder (over the acromioclavicular joint) and back to the platform. An additional set of three shoulder elevation exertions was performed with arms abducted 90° in the frontal plane to ensure maximum values were reached. Each MVC was performed three times at approximately three seconds per trial. MVC data were recorded and used for analysis and to normalize surface electromyography (sEMG) from the testing sessions.

Prior to testing initiation, each subject's maximum reach distance was measured. The reach distance was measured from the acromio-clavicular joint to the distal metacarpals. Subjects were placed in front of the apparatus with the telescoping pole placed on their manubrium to ensure accurate distance. This distance was determined using the reach distance percentage for each subject. For each posture, subjects were positioned according to all three variables (height, angle, reach). The telescoping pole helped the subjects maintain the proper distance and posture. Subjects were then asked to exert the maximum force capable for the specified condition, as described in section 3.1.

3.3 Data Collection

All instrument data were collected on personal computers. Each computer was equipped with a 12-bit resolution Analog to Digital (A/D) conversion card (National Instruments, Austin, TX). All instrument data collected were processed using custom designed software developed using LabVIEW (version 5.1) (National Instruments, Austin, TX).

3.3.1 Triaxial Load Cell

All force measurements were obtained using a 500 lbs Triaxial Load Cell (500 lb XYZ Sensor, Sensor Development Inc., Lake Orion, MI). Force data were sampled at 1000 Hz.

3.3.2 sEMG Data

All sEMG signals were processed through a differential amplifier (gain = 1000 to 5000, input impedance = 10 GΩs, 10-1000 Hz, CMRR = 115 dB at 60 Hz, Bortec, Octopus AMT-8, Calgary, Canada). sEMG signals were digitally sampled at 2048 Hz.

3.4 Data Analysis

The dependant variables in this study include: the amplitude of maximum force, and the corresponding peak muscle activation levels during each exertion (measured with EMG). The independent variables are; the height of the exertion, the angle in the transverse plane, the reach and the direction of the exertion.

EMG data were collected and bandpass filtered (20-1000 Hz), full-wave rectified and low-pass filtered using a 2nd order Butterworth filter with a frequency cut-off of 2 Hz. These data were analyzed in conjunction with the outputs from the triaxial load cell enabling muscle activation levels to be compared to force output. For each subject, the EMG_{PK}, for the two trials in each condition, were used in the Analysis of Variance (ANOVA). An ANOVA with repeated measures ($p<0.05$) was used to determine any statistically significant effects in the current 3 x 3 x 2 study design (Figure 15).

For each subject, the peak force of the two trials for each condition was used in the ANOVA. An ANOVA with repeated measures ($p<0.05$, height, angle, reach) was used to determine any statistically significant differences in the current 3 x 3 x 2 study design (Figure 15). There was not data collected in all three heights and in both reach distances for the exertions located at -20° across the body (at the midline). One value was tested in this plane of action. The hand position was located at shoulder height and at 80% of the arm reach. This value was included to provide insight into any strength trends which may exist beyond other tested hand positions. The positions not included were done so, due to the awkward location of the exertion, and/or the potential for discomfort and muscle fatigue.

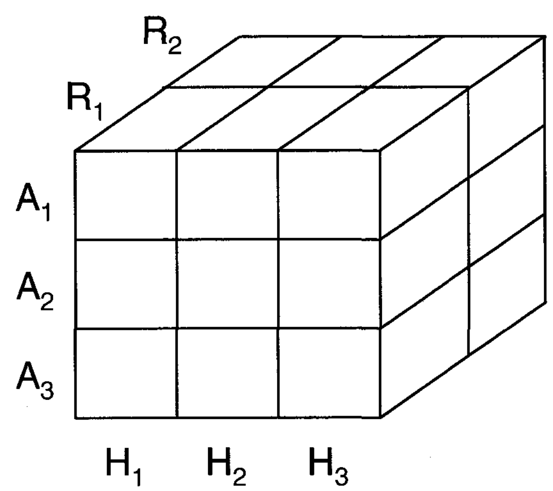

Figure 15: Study design. 3 x 3 x 2 at push forward, where H is height, A is angle and R is reach. There were 5 additional 3 x 3 x 2 cubes tested as well (1 per direction).

Statistically significant interactions between independent variables, identified by the ANOVA, were further analyzed using a Tukey's Honestly Significant Differences Post hoc analysis. This test demonstrates where the differences in the data are present. If multiple effect interaction levels are found, the order of importance was, (from least to greatest) direction, reach, angle and height. In the event that no significant interactions were found between variables, individual variable main effects were identified. Where there are more than 2 levels within a dependant variable, further analysis was conducted using a Tukey's significant difference Post hoc analysis determined where the significant difference occurs.

3.4.1 Regression Equations

The final goal of this study was to develop a regression based model or tool. This tool would be used to predict the maximal strength capabilities at the hand given the three dimensional distance to the manubrium. These equations were calculated using the variables of height, reach, angle and direction from a subset of the subject sample (20 subjects). Multiple regression equations were developed for each of the directions tested giving a 3x3x2 data set. The data were inputted into Stats View (SAS Institute Inc., 1997) for multiple regression analysis. The values generated using the variables were then compared against those recorded from the current study from the other subset of subjects (10), whose data was not used to generate the equations. The validity of these equations depends on the RMS error as a percentage of the mean. The lower this value, the more accurately the equation predicts the strength value. An RMS error of less than 10% and an $r^2 \geq 95\%$ indicated a good fit.

Chapter 4: RESULTS

The results of this study are divided into four sections. The first describes the kinetic data collected and the second will look at the EMG data. The third section will present the age effects and the fourth will focus on the regression model. Statistically significant differences ($P \leq .05$) have been further analyzed using Post Hoc analysis methods.

4.1 Maximum Voluntary Forces

The main dependant variable in the study was the amplitude of the maximum forces in each direction. All significant effects and interactions of height, angle and reach, on maximum force, are shown in Table 9. In cases where there were three way interactions between height, angle and reach, the two way interactions between height and angle will be described for both the 40% and 80% heights. Main effects are presented in Figure 16 for all six directions tested.

Table 9: Repeated measures ANOVA results for maximal force data. Significance values are presented and the highest level interactions are underlined and bolded for each variable.

	Height	Angle	Reach	Height * Angle	Height * Reach	Angle * Reach	Height * Angle * Reach
Push	0.0100	0.0001					***0.01***
Pull	0.01	0.0001	0.01	***0.001***		***0.0001***	
Push Up	0.0001		0.0001				***0.0001***
Push Down	0.0001	0.0001	0.05				***0.05***
Medial	0.0001	0.0001	0.01		***0.0001***	***0.0001***	
Lateral	0.0001	0.0001	0.05				***0.0001***

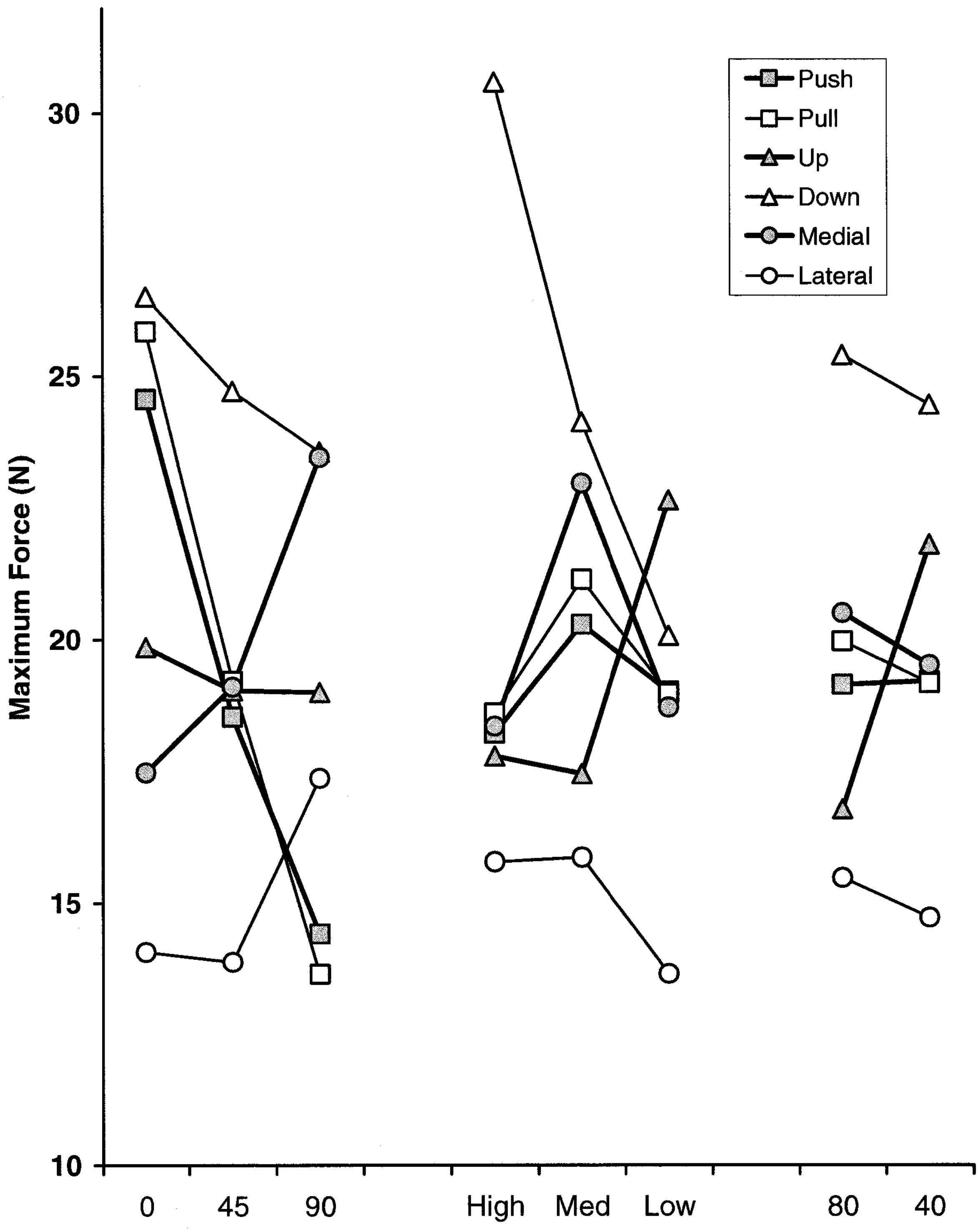

Figure 16: The main effects of all variables (height, angle, and reach) on maximum force production across all conditions for each of the six directions.

4.1.1 Push Forward

A three way interaction ($p < 0.01$) was found between height, angle, and reach.

40% Reach: At an angle of 0°, the force recorded at low and medium heights were 12% and 16% higher, respectively, than at the high height. At 45°, the medium height forces were 12% and 13% higher than the low and high heights, respectively. At 90°, there were no significant differences between the three heights (Figure 17).

80% Reach: At an angle of 0°, forces recorded at medium height were 14% greater than those at low height and 7% greater than those at high height. At 45°, forces at medium height were greater than those at low and high by 10% and 16%, respectively. Finally, at 90°, there were no significant differences between the three heights.

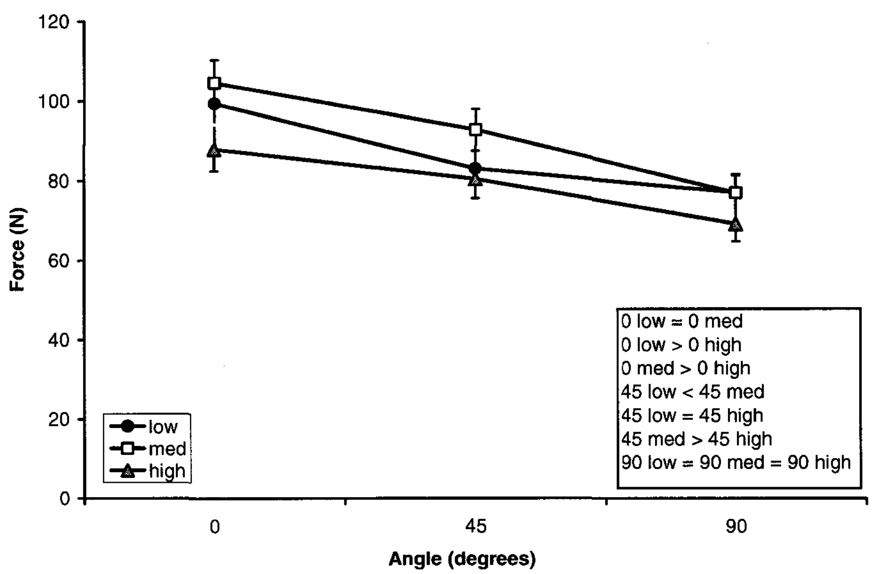

Figure 17: The height x angle interaction for push force at the 40% reach. (n=29). Standard error bars are presented. Post hoc results are presented.

4.1.2 Pull Backward

There was a significant two-way interaction between height and angle ($p < 0.001$). At 0°, maximum forces at medium height were 18% and 17% higher than at low or high heights, respectively. At 45°, forces at medium height were 10% higher than at the high height. There was also a significant interaction between angle and reach ($p < 0.0001$, Figure 18). At 0°, the 80% reach pull forces were 23% greater than at 40% reach. At 45°, there was no effect of reach. At 90°, the 40% reach forces were 24% greater that at 80% reach.

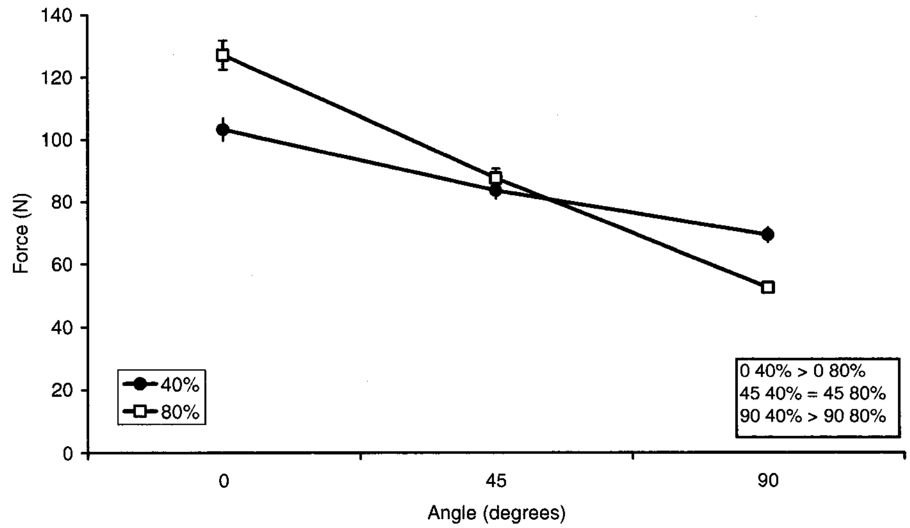

Figure 18: The angle x reach interaction for pull force (n=87). Standard error bars are presented. Post hoc results are presented.

4.1.3 Push Up

A three-way interaction ($p < 0.0001$) was found between height, angle, and reach.

<u>40% Reach</u>: At 0°, the forces recorded at low height were greater than those at both medium and high heights by 9% and 26%, respectively. Forces at medium height were 18% greater than at those at high height. At 45°, the forces at low height were greater than those at both medium and high heights by 17% and 23%, respectively. Finally, at 90°, the forces recorded at low height were 21% and 24% greater than those at medium and high heights, respectively (Figure 19).

80% Reach: At 0°, the forces recorded at low height were greater than those at medium and high heights by 36% and 33% respectively. At 45°, the forces at low height were greater than both those at medium and high heights by 30% and 22%, respectively. Finally, at 90°, the forces at high height were found to be greater than those at medium height by 48%. Forces at low height were greater than at medium height by 28% (Figure 20).

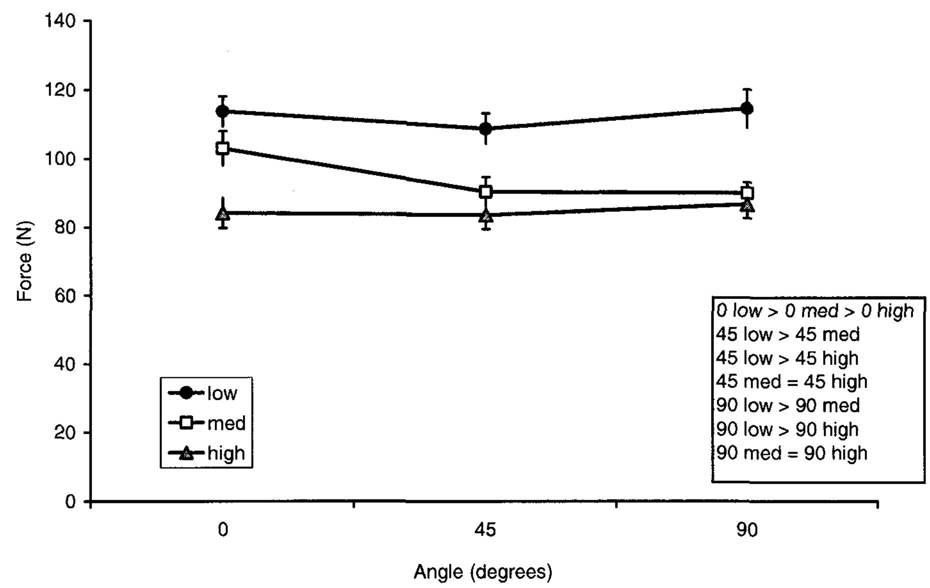

Figure 19: The height x angle interaction for push up 40% reach. (n=29). Standard error bars are presented. Post hoc results are presented.

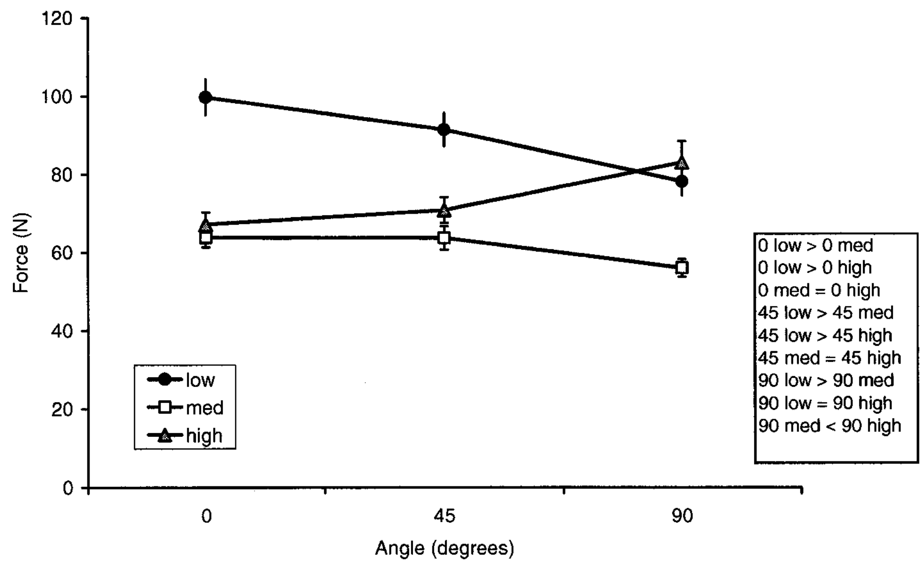

Figure 20: The height x angle interaction for push up 80% reach. (n=29). Standard error bars are presented. Post hoc results are presented.

4.1.4 Push Down

A three-way interaction ($p < 0.05$) was found between, height, angle and reach (Figure 21, Figure 22).

40% Reach:, At 0°, the forces recorded at high height were greater than those at both medium and low heights by 63% and 80%, respectively. At 45°, the forces at high height were 62% and 83% higher than those at medium and low heights, respectively. Finally at 90°, the forces at high height were 100% and 96% greater than at medium and low heights, respectively. No significant differences occurred between low and medium height at any angle.

80% Reach: At 0°, there were no significant differences between the three heights. At 45°, the forces at high and medium heights were 35% and 53% greater, respectively, than at low height. At 90°, the forces at high and medium heights were 29% and 38% greater, respectively, than at low height. Differences were not significant between medium and high heights at any angle.

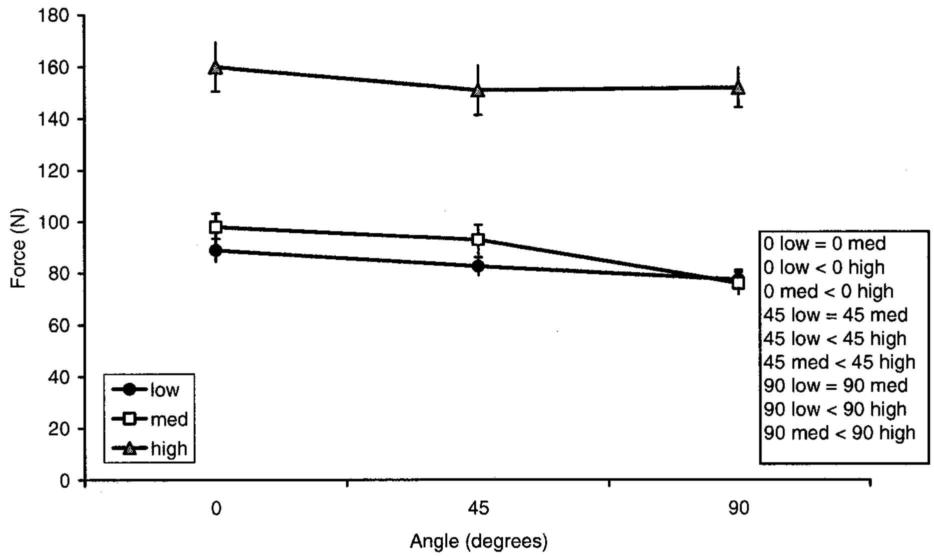

Figure 21: The height x angle interaction for push down force at 40% reach. (n=29). Standard error bars are presented. Post hoc results are presented.

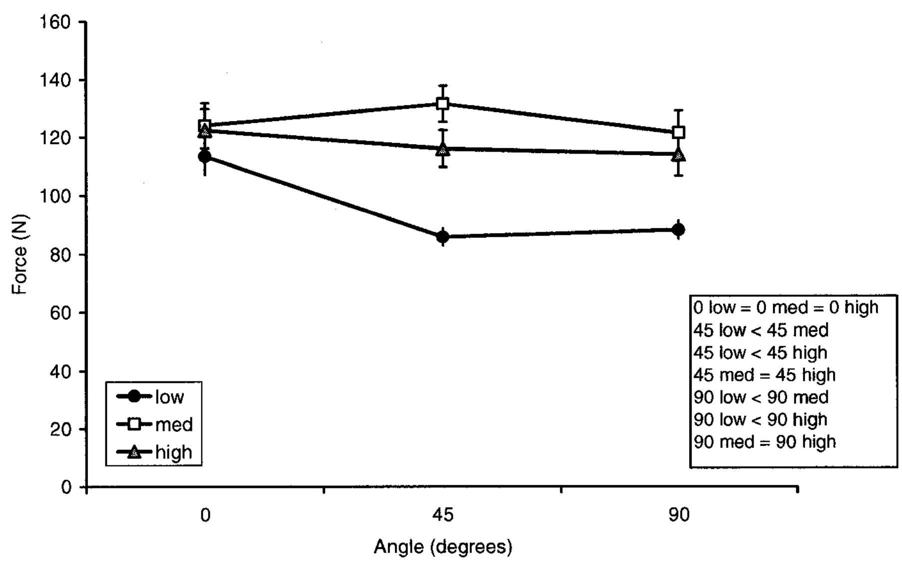

Figure 22: The height x angle interaction for push down force at 80% reach. (n=29). Standard error bars are presented. Post hoc results are presented.

4.1.5 Medial

There was a significant two-way interaction between height and reach ($p < 0.0001$, Figure 23). At 40% reach, maximum forces at medium height were 20% greater than at high height and 37% greater than at low height. Forces at high height were 9% greater than at low height. At 80% reach, maximum forces at medium height were 20% greater than at high height and 11% greater than at low height. Forces at low height were 11% greater than at high height.

There was also a significant two-way interaction between angle and reach ($p < 0.0001$, Figure 24). At 0°, the 40% reaches were 20% greater than at 80% reach. At 45°, there were no significant differences. At 90°, the 80% reaches were 31% greater than at 40%.

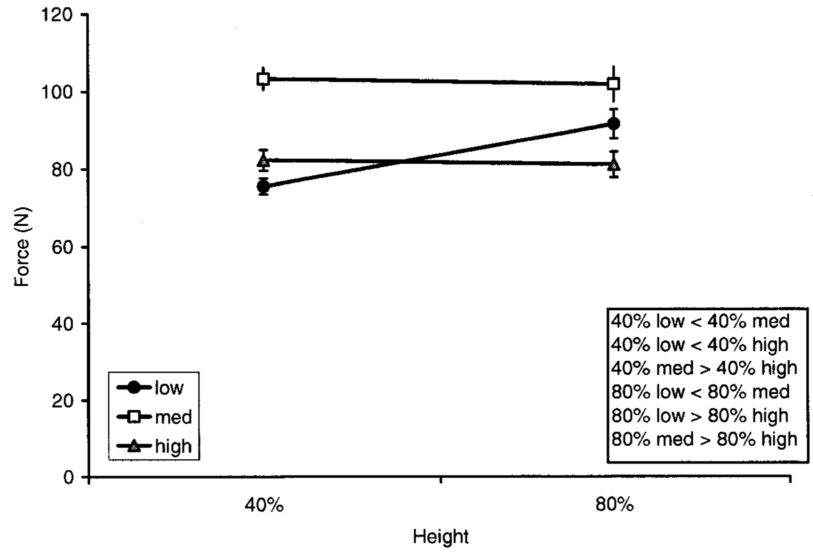

Figure 23: The height x reach interaction for the medial direction. (n=87). Standard error bars are presented. Post hoc results are presented.

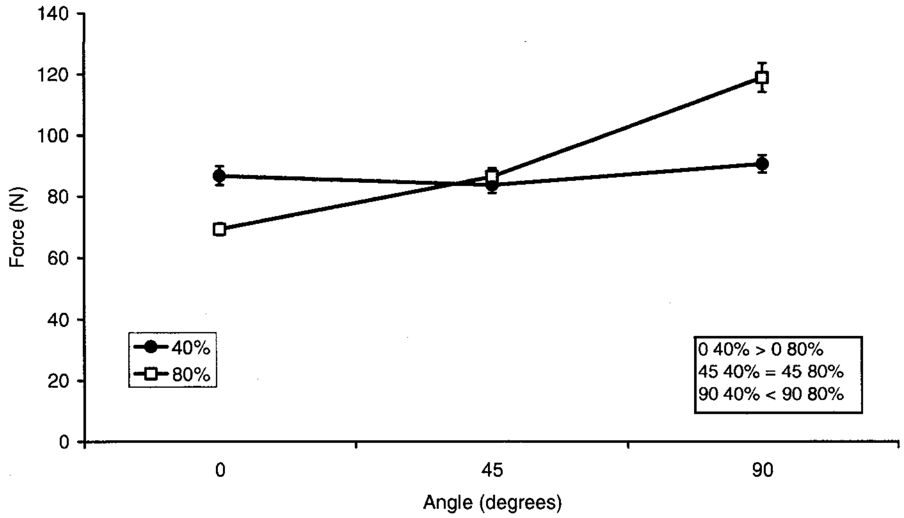

Figure 24: The angle x reach interaction for the medial direction. (n=87). Standard error bars are presented. Post hoc results are presented.

4.1.6 Lateral

A three way interaction was found between height, angle, and reach ($p < 0.0001$).

<u>40% Reach</u>: At 0°, forces recorded at high and medium heights were greater than low height by 41% and 47%, respectively. At 45°, forces recorded at high and medium heights were greater than low height by 21% and 20%, respectively. At 90°, there were no significant differences between the three heights (Figure 25).

<u>80% Reach</u>: At 0°, there were no significant differences between the three heights. At 45°, there were no significant differences between the three heights. At 90°, forces recorded at high and medium heights were greater than at low height by 25% and 22% respectively.

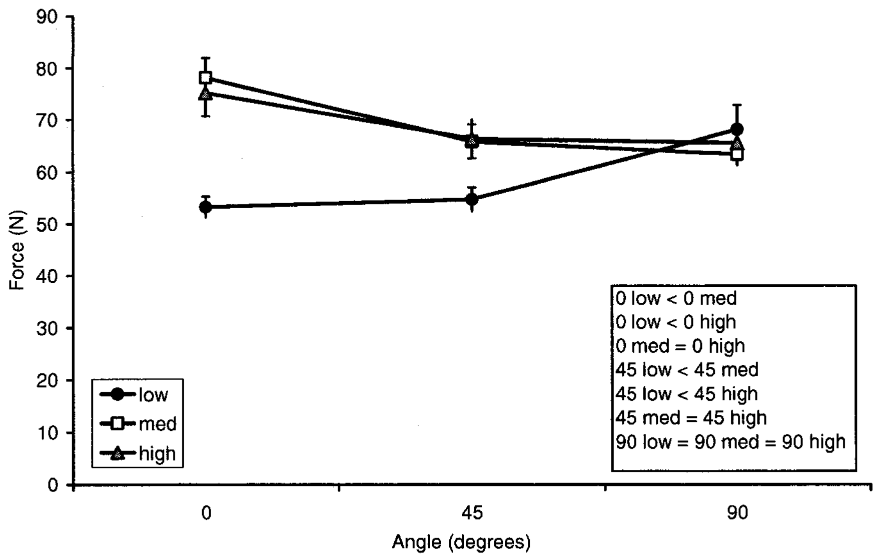

Figure 25: The height x angle interaction for lateral force at 40% reach. (n=29). Standard error bars are presented. Post hoc results are presented.

4.1.7 Exertions at -20°

There were also exertions performed across the midline at -20° to the sagittal shoulder plane (0°), at both low and high heights and 80% reach. These exertions were compared to those at 0° using t-tests ($p < 0.05$). Six relationships were found to be significantly different out of a possible 12. The force for trials across the midline were found to be significantly higher than at 0° for the following conditions: push forward direction at low height (by 28%), medial direction at high height (12%) and low height (14%), lateral direction at high height (16%) and low height (17%). For the pull backward direction at low height, -20° exertions were 16% lower than exertions at 0°.

4.2 EMG Data

The EMG dependant variable was the peak amplitude for each muscle during each effort. All significant main and interaction effects are shown in Table 10. Table 11 presents the means of the peak activations for all muscles and conditions (refer to Appendix C for standard deviations). For each direction, the one or two muscles, that were consistently found to have the maximum activations, will be described in greater detail. For the dominant muscles listed below, in which the significant effects are not described here, please refer to Appendix C for EMG graphs.

Table 10: Repeated measures ANOVA results for EMG data. Significance values are presented and the highest level interactions are underlined and bolded for each variable

		Height	Angle	Reach	Height * Angle	Height * Reach	Angle * Reach	Height * Angle * Reach
Push	BB	0.05			***0.01***			
	TB	0.0001	0.0001		***0.0001***	***0.05***		
	DA	0.001						***0.05***
	DL		0.0001					***0.001***
	TR	0.0001		0.01				***0.05***
Pull	BB	0.0001	0.001	0.01	***0.0001***	***0.05***		
	TB	0.05	0.0001		***0.05***			
	DA	0.0001		0.05	***0.0001***	***0.05***		
	DL	0.0001	0.0001		***0.01***	***0.001***	***0.0001***	
	TR	0.0001		***0.05***	***0.0001***			
Push Up	BB	***0.01***						
	TB	0.0001				***0.05***		
	DA	0.0001	0.01	0.01	***0.01***	***0.01***	***0.05***	
	DL	0.0001	0.0001	0.0001	***0.001***	***0.01***	***0.001***	
	TR	0.0001	0.0001	***0.001***	***0.01***			
Push Down	BB	0.01	0.01	0.001	***0.01***	***0.01***		
	TB	0.0001		0.05		***0.0001***		
	DA	0.0001	0.0001	0.05				***0.05***
	DL		0.0001					***0.05***
	TR	0.01			***0.01***	***0.05***		
Medial	BB	0.0001	0.001					***0.01***
	TB	***0.01***	***0.05***					
	DA	0.0001	0.0001			***0.0001***	***0.05***	
	DL	0.0001	0.05	0.05				***0.01***
	TR	0.0001	0.0001	***0.001***	***0.001***			
Lateral	BB	***0.0001***						
	TB	0.001	0.01					***0.05***
	DA	***0.01***		***0.001***				
	DL	0.01	***0.001***	0.001		***0.001***		
	TR					***0.05***		

Table 11: The means of the all peak EMG amplitudes are presented for each muscle for each condition in all six directions. Cells bolded and highlighted indicate the muscle(s) with the highest activation for the condition and direction. Note, for each direction, that there are generally one or two muscles that always had the highest activity.

		High (head)						Med (shoulder)						Low (waist)					
		0°		45°		90°		0°		45°		90°		0°		45°		90°	
		80%	40%	80%	40%	80%	40%	80%	40%	80%	40%	80%	40%	80%	40%	80%	40%	80%	40%
Push Forward	BB	7.8	11.7	12.0	11.1	13.5	15.7	12.2	12.4	14.5	17.0	14.8	15.7	19.9	18.5	14.7	18.0	14.9	15.3
	TB	**27.0**	25.1	13.4	18.2	11.9	15.8	**30.6**	**27.6**	13.6	13.9	10.9	10.8	12.2	10.3	9.6	9.6	9.4	9.0
	DA	14.7	20.5	**23.4**	**23.8**	**25.2**	27.2	28.5	24.3	**30.3**	**25.7**	**26.2**	**25.1**	**40.2**	**29.6**	**34.3**	**34.0**	**29.7**	**31.1**
	DL	9.5	20.7	21.2	19.6	21.3	24.0	12.6	10.4	20.2	17.6	20.4	21.6	16.4	11.4	19.1	16.2	15.6	14.9
	TR	18.1	**27.2**	21.3	23.3	21.6	**28.9**	17.6	23.1	19.3	21.4	18.4	20.8	13.4	9.9	11.9	11.4	11.3	12.1
Pull Backward	BB	22.7	23.9	15.8	17.7	15.2	20.0	**29.0**	**37.0**	11.0	19.6	12.9	18.8	5.2	6.2	6.3	6.8	8.5	9.5
	TB	16.1	17.5	20.6	18.6	21.6	19.1	10.8	9.3	12.8	7.9	20.3	13.5	**16.1**	17.0	15.8	15.9	21.0	21.2
	DA	26.6	24.1	22.3	19.0	20.4	16.2	10.5	11.0	14.7	12.9	16.8	14.1	4.6	7.4	8.8	8.7	10.7	11.7
	DL	33.3	31.4	**54.6**	**41.1**	**55.0**	**37.5**	11.7	22.3	**41.2**	**32.9**	**46.7**	**38.1**	14.1	**24.6**	**25.1**	**27.9**	**31.9**	**39.6**
	TR	**34.1**	**32.8**	31.8	29.9	28.9	28.5	20.4	21.4	23.6	18.0	24.4	21.2	6.2	7.0	8.1	8.6	12.4	12.6
Push Up	BB	16.6	15.5	17.9	15.4	18.1	14.6	24.0	26.9	22.4	27.5	21.6	32.5	**31.3**	**28.9**	**27.9**	**32.4**	24.3	**28.1**
	TB	18.6	21.0	19.3	19.3	18.2	19.6	15.2	10.4	14.4	9.7	14.0	10.1	9.1	7.9	9.6	8.7	9.7	8.7
	DA	**53.2**	**50.0**	**43.8**	**52.2**	**46.6**	**45.2**	**52.3**	**41.4**	**44.3**	**44.3**	36.8	**37.7**	22.0	15.2	26.7	20.4	24.0	14.9
	DL	31.8	24.9	38.0	25.8	42.0	24.6	19.7	14.5	29.6	21.2	**41.1**	23.4	13.1	9.5	21.3	14.9	24.9	16.7
	TR	33.2	30.8	37.3	32.9	38.3	33.4	28.4	22.0	36.2	33.9	39.8	34.8	19.1	17.1	25.6	20.9	**25.2**	24.9
Push Down	BB	8.9	**19.1**	6.7	11.3	7.5	**17.4**	4.7	5.8	5.5	5.5	5.7	4.8	7.5	7.7	6.4	8.2	7.3	6.7
	TB	**20.8**	13.6	**21.4**	**16.2**	**19.5**	11.9	**24.1**	**16.8**	**27.1**	**19.6**	**26.8**	**19.9**	**38.3**	**41.3**	**34.5**	**41.0**	**32.6**	**40.1**
	DA	14.7	12.7	10.8	13.7	10.2	10.9	10.3	6.4	8.8	5.4	6.0	4.5	6.6	7.4	4.8	5.3	4.2	4.6
	DL	7.8	7.1	8.8	7.5	12.2	8.6	9.8	11.5	7.0	6.5	8.2	6.1	13.9	14.8	7.4	8.8	4.7	7.8
	TR	9.0	10.8	9.0	9.5	10.2	11.5	7.7	6.0	9.9	7.5	8.7	7.7	8.4	7.4	7.1	7.6	5.8	7.3
Medial	BB	26.9	24.0	33.9	30.3	33.2	37.1	24.7	**29.8**	**30.2**	**46.6**	**26.7**	**57.8**	11.3	**10.2**	**14.5**	**10.0**	**12.1**	8.7
	TB	14.3	15.8	14.4	14.3	14.3	15.3	11.8	8.3	9.1	9.8	8.3	11.3	7.4	6.5	8.5	9.0	10.2	**12.4**
	DA	**40.9**	**38.2**	**35.1**	**41.2**	31.7	**39.7**	**28.7**	25.1	22.0	23.3	13.3	18.6	**13.1**	8.0	10.4	6.3	5.5	4.4
	DL	20.4	26.8	21.8	23.5	29.2	26.2	10.1	13.1	12.7	16.5	12.2	18.1	3.1	2.9	4.0	4.3	3.5	4.4
	TR	28.1	33.0	27.8	32.1	**38.9**	36.4	15.7	20.3	18.8	20.4	18.6	23.9	4.3	4.5	4.3	4.4	4.0	5.0
Lateral	BB	10.3	13.1	8.7	10.3	10.6	9.2	13.9	14.6	13.9	13.1	11.0	12.7	19.6	18.2	16.8	21.7	16.0	23.9
	TB	31.8	**28.7**	**37.3**	**37.4**	**36.9**	**35.2**	27.3	20.9	32.8	**28.6**	20.1	**29.2**	25.8	23.2	18.0	23.1	15.0	20.7
	DA	13.5	10.9	12.9	12.0	12.5	10.7	16.6	13.4	15.4	13.5	15.4	10.3	17.2	17.5	16.9	16.3	20.7	18.0
	DL	**32.1**	22.9	23.3	21.1	21.6	15.3	**37.3**	**28.3**	**37.6**	24.4	**29.3**	14.3	**37.5**	**33.7**	**30.0**	**30.8**	**28.6**	**31.9**
	TR	13.2	14.1	12.4	11.8	12.7	12.2	16.6	14.7	17.0	14.8	16.2	11.4	16.3	15.6	15.2	14.4	14.5	17.5

4.2.2 Push Forward EMG

Anterior Deltoid: There was a three-way interaction between height, angle and reach ($p < 0.05$). At 40% reach (Figure 26), peak EMG amplitude (EMG_{PK}) tended to increase from high to medium to low height, although this was not significant at 90°. At 80% reach (Figure 27), the same trend existed at 0° but the differences were diminished by 90°.

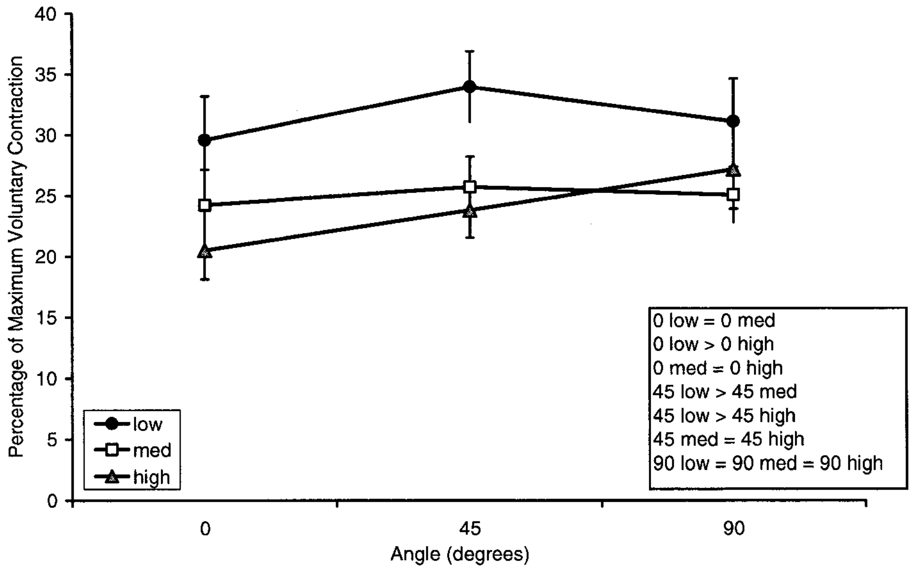

Figure 26: The height x angle interaction for DA during pushing forward at 40% reach. (n=16). Standard error bars are presented. Post hoc results are presented.

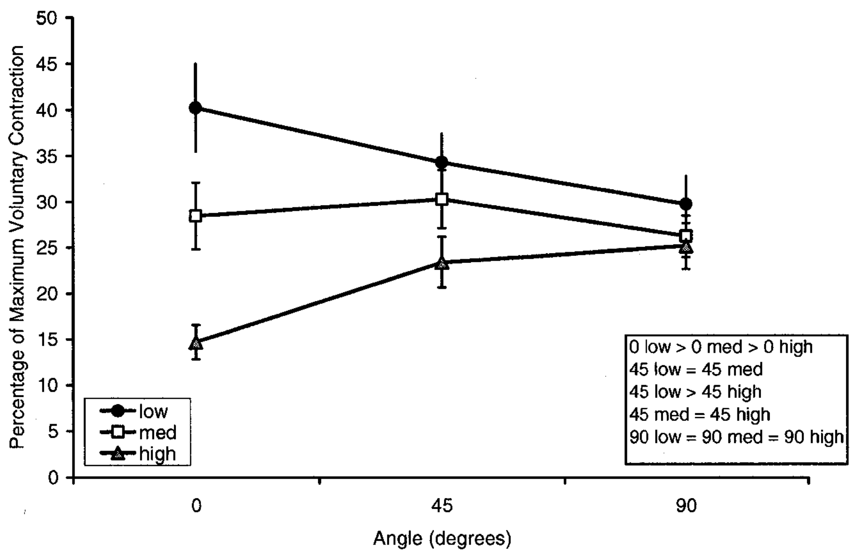

Figure 27: The height x angle for DA during pushing forward at 80% reach. (n=16). Standard error bars are presented. Post hoc results are presented.

4.2.3 Pull Backward EMG

Lateral Deltoid: There were three two-way interactions. The first was a two-way interaction ($p < 0.01$) between height and angle (Figure 28). Exertions recorded at the high height displayed the highest EMG_{PK} across all three angles. Furthermore, EMG_{PK} showed an increasing trend as the angle increased.

The second two-way interaction ($p < 0.001$) was between height and reach (Figure 29). At 80% of the full reach, exertions at high height displayed the greatest EMG_{PK} showed an increase in EMG_{PK} for the 40% reach condition. Exertions at low height displayed the lowest EMG_{PK} and showed a decrease in activation from the 40% reach condition.

The third two-way interaction ($p < 0.0001$) was between angle and reach (Figure 30). At 0°, EMG_{PK} at 40% reach was found to be 25% greater than 80% reach. At 45°,

EMG_{PK} at 80% reach was 19% greater than those at 40% reach. At 90°, EMG_{PK} at 80% reach was 16% greater than those at 40% reach. In addition, as angle increased the EMG_{PK} at both reach distances did as well.

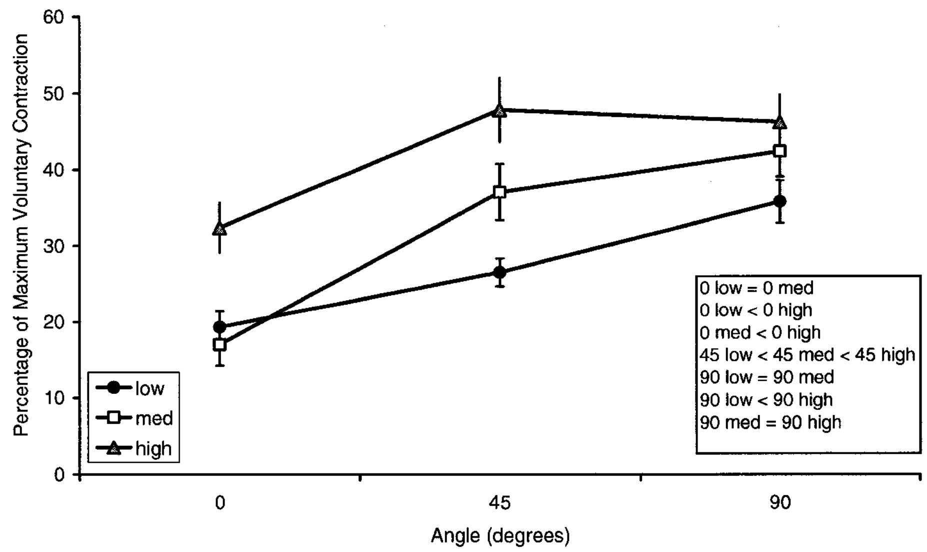

Figure 28: The height x angle interaction for DL in the pull direction. (n=34). Standard error bars are presented. Post hoc results are presented.

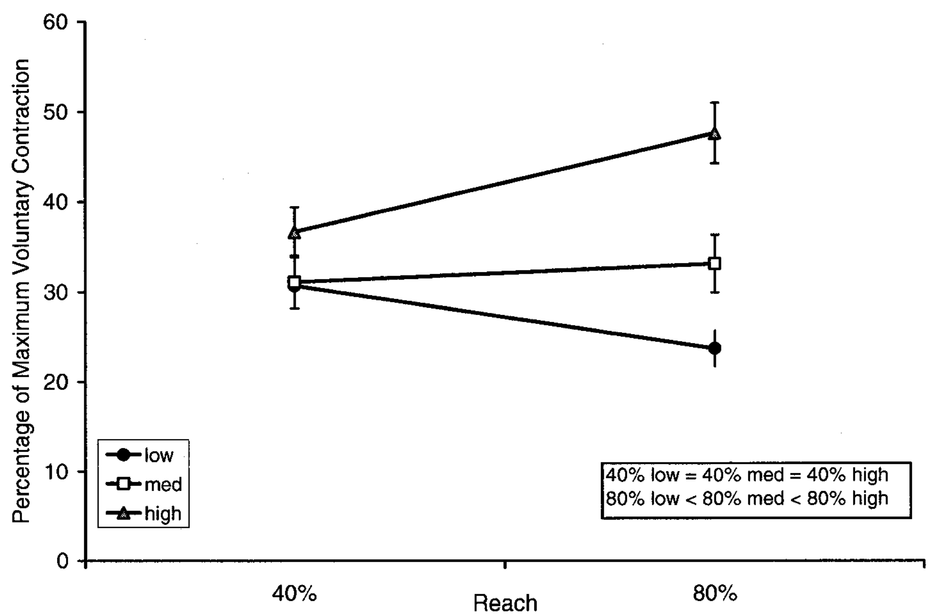

Figure 29: The height x reach for DL in the pull direction. (n=34). Standard error bars are presented. Post hoc results are presented.

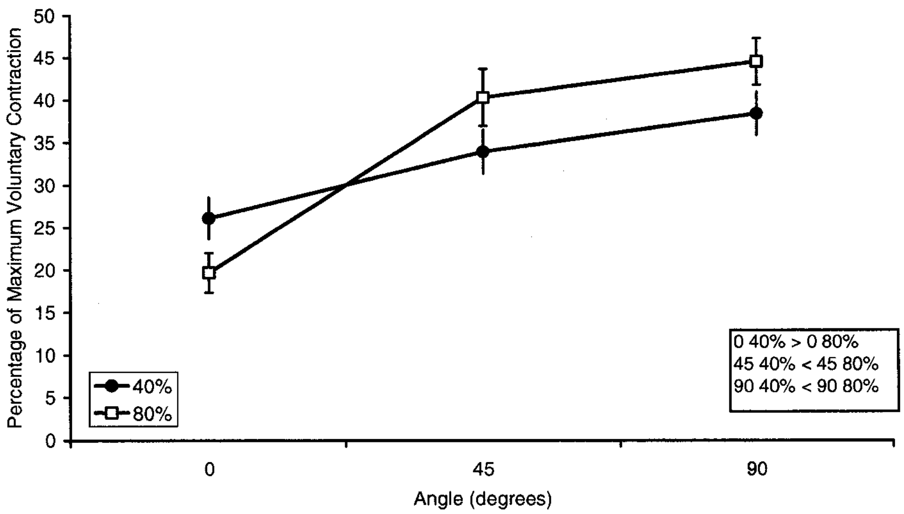

Figure 30: The angle x reach interaction for DL in the pull direction. (n=51). Standard error bars are presented. Post hoc results are presented.

4.2.4 Push Up EMG

Anterior Deltoid: There were three significant two-way interactions found for DA in the push up direction. The first two-way interaction ($p < 0.01$) was between height and angle (Figure 31). Across all three angles, the highest EMG_{PK} was seen at high height and the lowest were at the low height. EMG_{PK} also decreased as angle increased for exertions at both medium and high heights.

The second significant two-way interaction ($p < 0.01$) for the DA was between height and reach (Figure 32). At 40% reach, as height increased so did EMG_{PK}. For the conditions at 80% reach, it was found that both high and medium heights had EMG_{PK} that were greater than low height, by 98% and 84% respectively.

The third significant two-way interaction ($p < 0.05$) was between angle and reach (Figure 33). At 0°, EMG_{PK} at 80% reach was found to be 20% greater than those at 40% reach.

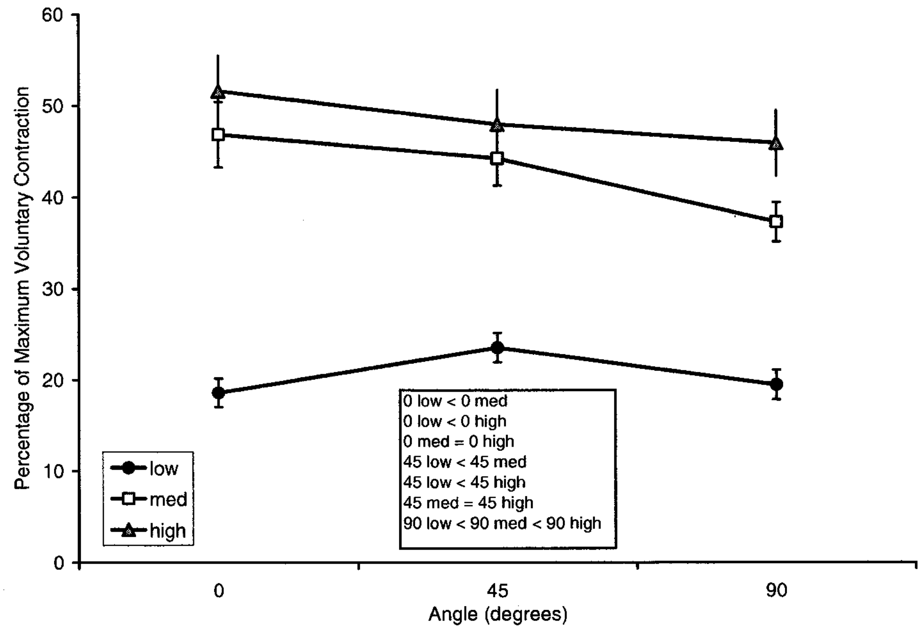

Figure 31: The height x angle interaction for DA in the push up direction. (n=32). Standard error bars are presented. Post hoc results are presented.

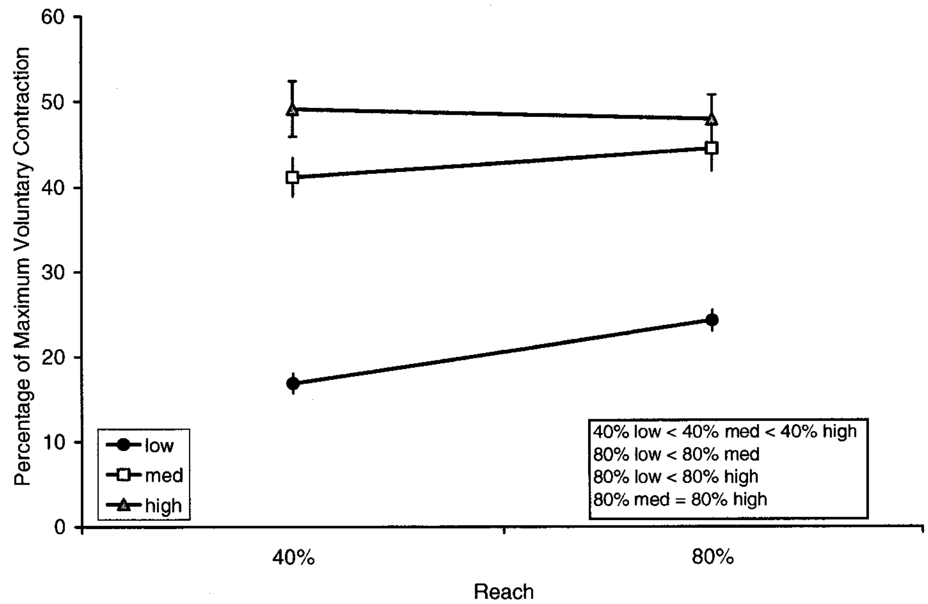

Figure 32: The height x reach interaction for DA in the push up direction. (n=48). Standard error bars are presented. Post hoc results are presented.

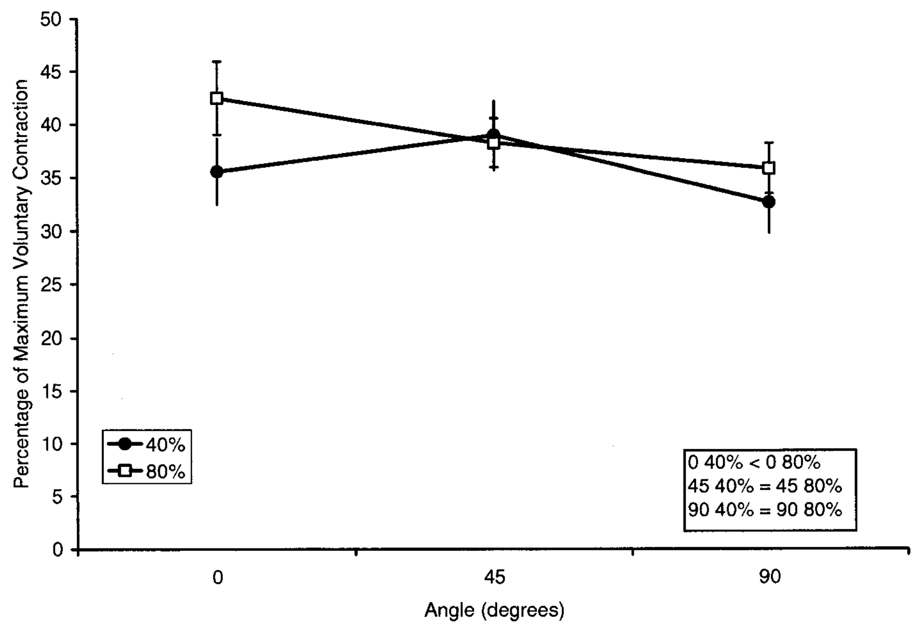

Figure 33: The angle x reach interaction for DA in the push up direction. (n=48). Standard error bars are presented. Post hoc results are presented.

4.2.5 Push Down EMG

Triceps Brachii: There was a two-way interaction ($p < 0.0001$) for TB identified between height and reach (Figure 34). At both 40% and 80% reach, EMG_{PK} increased as the height decreased. At 40%, EMG_{PK} at low height was found to be 54% greater than medium and 66% greater than at high heights. At 80%, EMG_{PK} at low height were found to be 26% greater than medium and 42% greater than high. EMG_{PK} at medium height were found to be 21% and 26% greater than at high height for 40% and 80% reach, respectively.

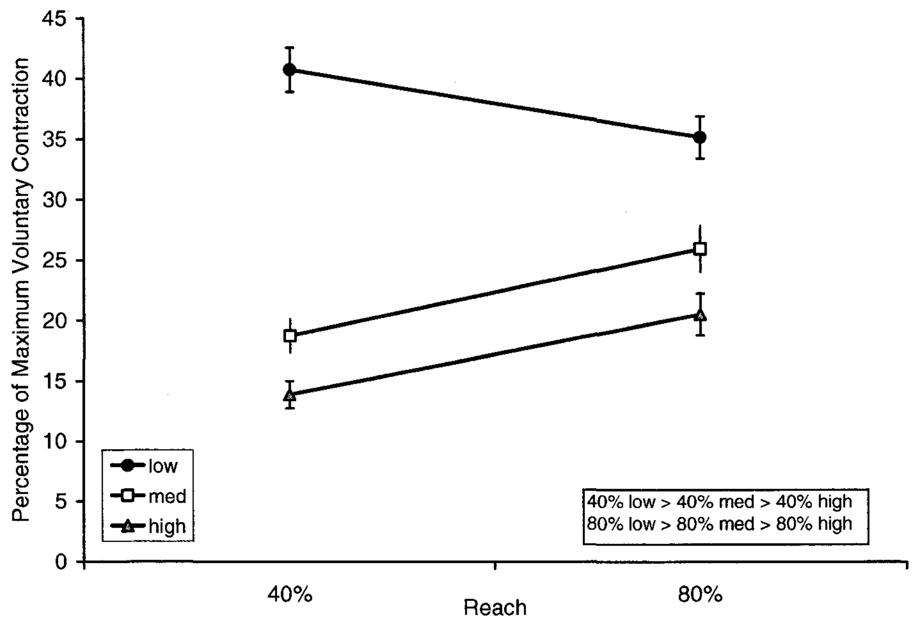

Figure 34: The height x reach interaction for TB in the push down direction. (n=51). Standard error bars are presented. Post hoc results are presented.

4.2.6 Medial EMG

It appeared that the biceps brachii was the dominant muscle in the low and medium heights and the anterior deltoid dominated at the highest height.

Biceps Brachii: There was a significant three-way interaction ($p < 0.01$) for BB between height, angle and reach in the medial direction (Figure 35, Figure 36).

40% reach: At 0°, EMG_{PK} at high and medium heights were greater than at low heights, by 135% and 193%, respectively. An increasing trend for EMG_{PK} at both high and medium heights was seen as angle increased. There was no corresponding increase for EMG_{PK} at low height. This created an increasing discrepancy between EMG_{PK} at high and low heights and between EMG_{PK} medium and low heights.

80% reach: At 0°, EMG_{PK} at both high and medium heights were greater than at low heights, by 139% and 119% respectively.

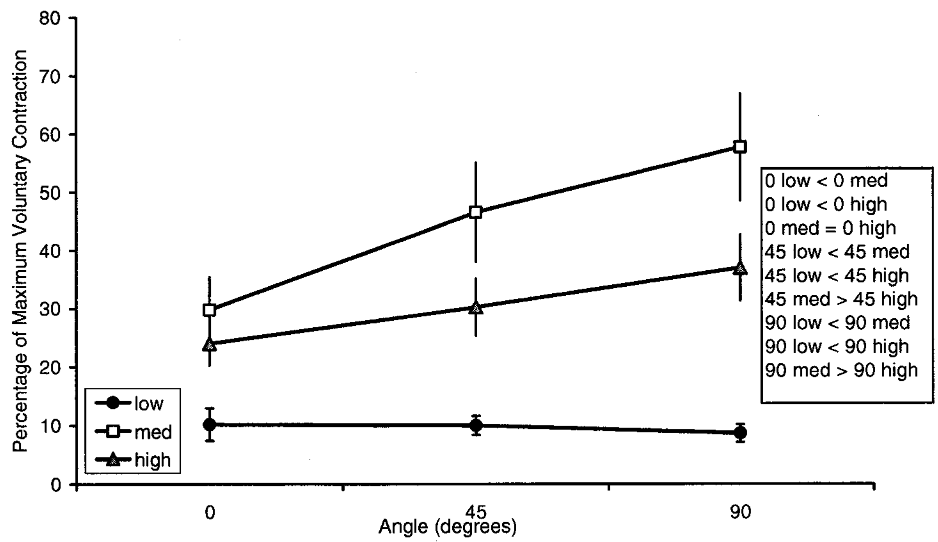

Figure 35: The height x angle interaction for BB in the medial direction at 40% reach. (n=11). Standard error bars are presented. Post hoc results are presented.

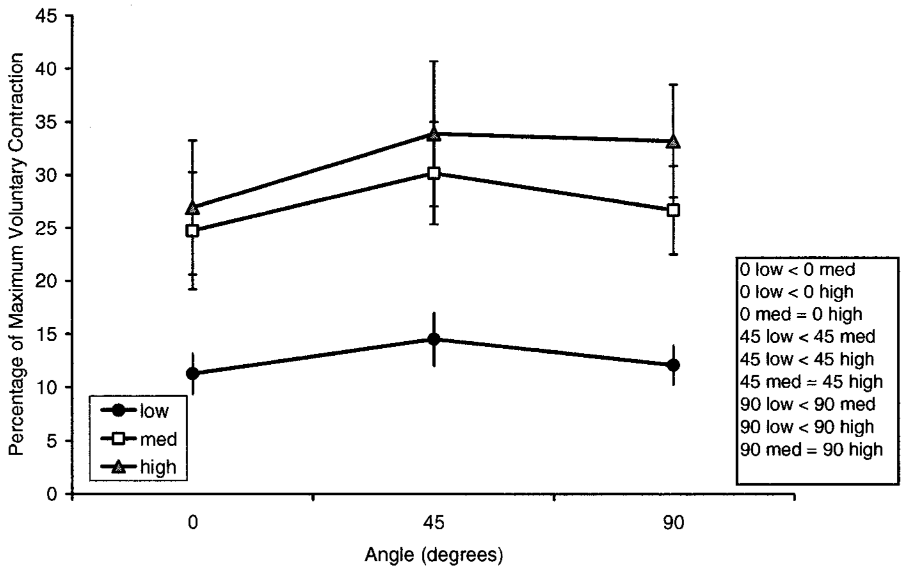

Figure 36: The height x angle interaction for BB in the medial direction at 80% reach. (n=11). Standard error bars are presented. Post hoc results are presented.

Anterior Deltoid: There was a significant two-way interaction ($p < 0.0001$) found for DA between height and reach in the medial direction. At 40% reach, EMG_{PK} at high height were much larger than at medium height which was subsequently much higher than at low heights. At 80%, a similar pattern existed although the differences between heights were somewhat lower.

There was a second significant two-way interaction ($p < 0.01$) found for DA between angle and reach. At 0°, EMG_{PK} at 80% reach was highest at 40% reach. At 45°, there were no differences between reaches and at 90° the 40% reach exertions were highest. In general, the 40% reach did not seem to be dependent on angle while the EMG_{PK} with 80% reach decreased steadily as angle was increased.

4.2.7 Lateral EMG

It appeared that the lateral deltoid was the dominant muscle in the low and medium heights and the triceps dominated at the highest height.

Triceps Brachii: There was a three-way interaction ($p < 0.05$) for TB found between height, angle and reach (Figure 37, Figure 38).

40% reach: At 0°, EMG_{PK} at high heights were 37% greater than medium. At 45°, EMG_{PK} at high heights was 62% greater than low, and 31% greater than medium. At 90°, EMG_{PK} at high heights were 70% greater than low and EMG_{PK} at medium were 41% greater than low.

80% reach: At 45°, EMG_{PK} at high heights were 107% greater than those at low height and EMG_{PK} at medium height were 82% greater than those at low heights. At 90°, exertions at high height were 146% greater than low and 83% greater than medium.

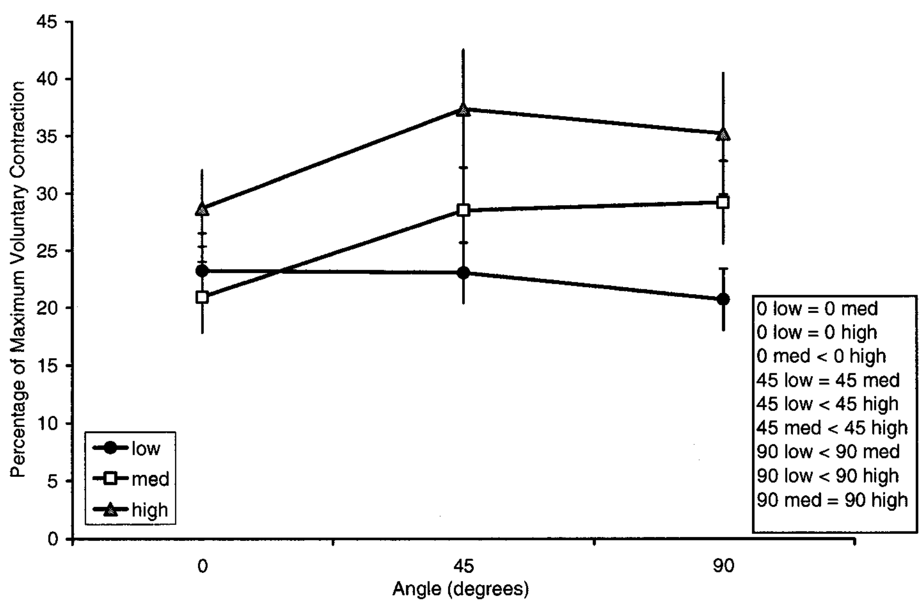

Figure 37: The height x angle interaction for TB in the lateral direction at 40% reach. (n=17). Standard error bars are presented. Post hoc results are presented.

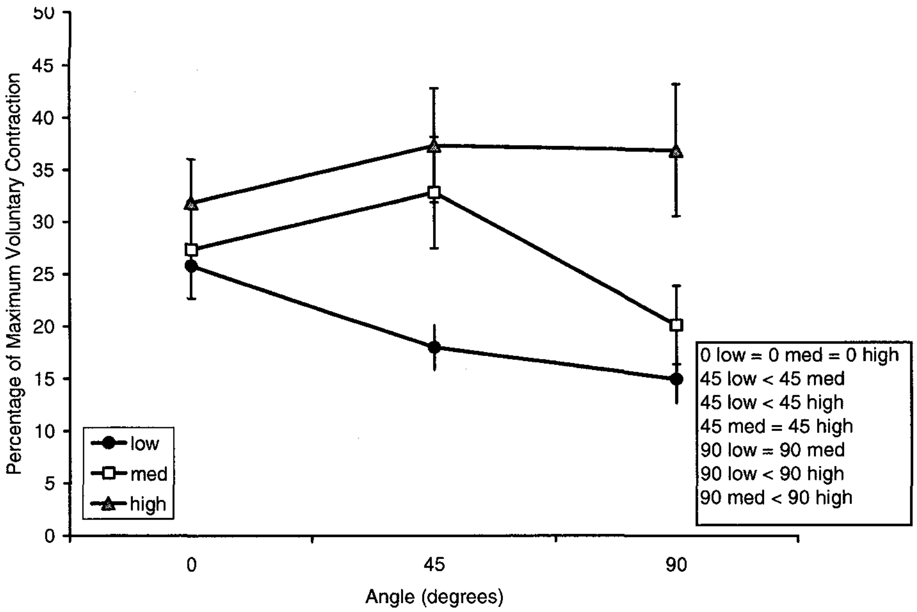

Figure 38: The height x angle interaction for TB in the lateral direction at 80% reach. (n=17). Standard error bars are presented. Post hoc results are presented.

Lateral Deltoid: There was a main effect ($p < 0.001$) of angle found for DL in the lateral direction (Figure 39). As angle increased, percentage EMG decreased. Exertions at 0° were 26% greater than those at 90°.

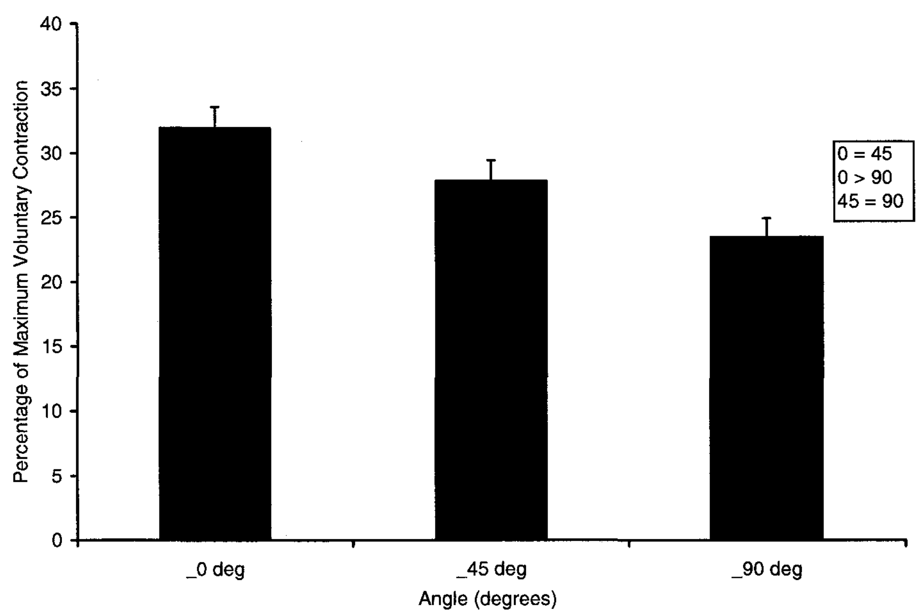

Figure 39: The main effect of angle for DL in the lateral direction. (n=102). Standard error bars are presented. Post hoc results are presented.

There was also a significant two-way interaction ($p < 0.001$) found between height and reach in the lateral direction (Figure 40). At 40%, EMG_{PK} at the low height was 31% greater than medium and 38% greater than exertions at high heights. At 80%, EMG_{PK} at medium height was 26% greater than at high heights. Furthermore, EMG_{PK} at low height were 20% greater than those at high.

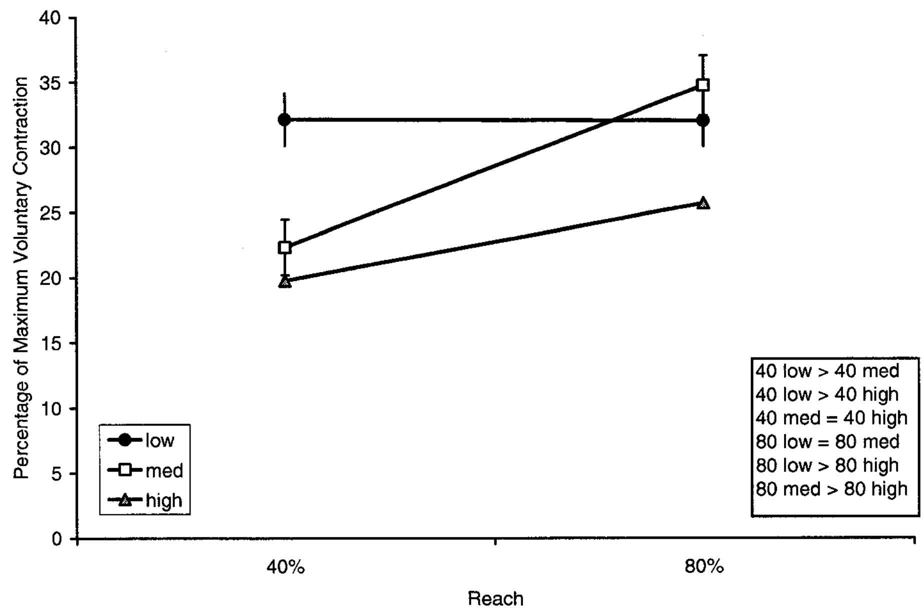

Figure 40: The height x reach interaction for DL in the lateral direction. (n=51). Standard error bars are presented. Post hoc results are presented.

4.3 Exertions at -20°

Exertions at -20° (across the midline) were compared to those postures at 0° of the same height and reach using t-tests. There were 12 comparisons made and six of them were found to be significantly different (Table 12).

Table 12: T-Tests results for exertions at -20° compared to those at 0°. Force means are presented as well as the percentage the exertions at -20° are different from those at 0°.

Direction	*Push Forward*		*Pull Backward*		*Medial*				*Lateral*			
Height	*Low*		*Low*		*High*		*Low*		*High*		*Low*	
Angle	*0°*	*-20°*	*0°*	*-20°*	*-20°*	*0°*	*-20°*	*0°*	*-20°*	*0°*	*-20°*	*0°*
Mean	79.3	**102.6**	**121.2**	102.3	63.7	**71.4**	70.1	**80.2**	56.3	**65.6**	54.9	**64.0**
Difference	-29%		16%		-12%		-14%		-16%		-17%	

4.4 Age Effects

An effort was made to recruit subjects from the whole range of ages seen in industry. Subjects were split into three groups using age as a between factors. There were no main effects found for age, but there were both significant two-way and three-way interactions found. For the purpose of this study however, only a selected few will be presented because the final recommendations to industry will be based results pooled across ages.

It was found that, for DL in the pull backward direction, there was a significant two-way interaction ($p < 0.01$) between height and age. For the 20s age group, exertions at the medium height were found to exhibit the lowest EMG_{PK}. For the 40+ age group the greatest EMG_{PK} was observed at the high height. There was also a two-way interaction ($p < 0.0001$) found for DL in the pull backward direction between angle and age. It was found that in all three angles, the greatest EMG_{PK} was produced by the subjects in the 40+ group.

There was a significant two-way interaction ($p < 0.05$) found for DL in the push up direction between height and age. As age increased, so did EMG_{PK}.

There was a significant two-way interaction ($p < 0.05$) found for DA in the push down direction between reach and age. Similar to the previously stated effects, the greatest EMG_{PK} was seen in the 40+ group but the lowest was in the 30s group, not the

20s group. For the 20s and 30s age groups, there was no change in EMG_{PK} from 40% to 80% reach, but there was a 17% increase going from 40% to 80% reach in the 40+ group (Figure 41).

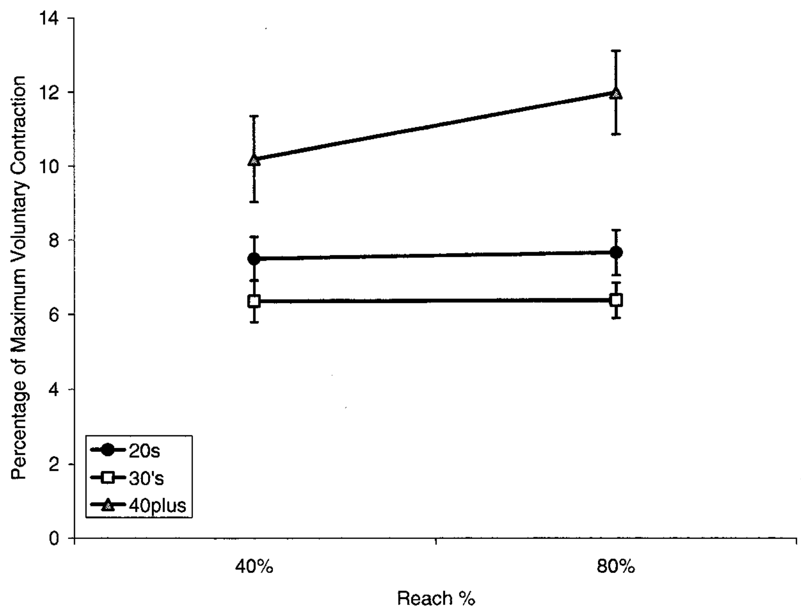

Figure 41: The reach x age interaction for DA in the push down direction. (n=54). Standard error bars are presented.

There was a two-way interaction ($p < 0.05$) for TB found between angle and age in the lateral direction. The largest activation levels were found across all three angles in the 30s age group. The lowest were found in the 20s age group. Furthermore, the 30s age group exhibited the highest EMG_{PK} at 45°.

4.5 Regression Model

There were two force regression equations developed for each of the six directions using a stepwise regression model. The equation was developed for all exertions at and above shoulder height and the second can be used for all exertions at or below shoulder height. The equations overlapped at shoulder height to ensure that the calculated values were similar. For each direction, there were values at shoulder height and when these were compared between the above and below shoulder equations, the mean RMS difference was only 5.4% and there was an r^2 of 94.6% indicating very good agreement (n=36). Table 13 shows both the significant input variables used in all 12 equations and the pertinent statistical information for each equation. The variables used in the equations were: the horizontal distance (H), vertical distance (V), and lateral distance (L) from the shoulder. In addition, H^2, V^2, L^2 and H*V, H*L, V*L were also used. These variables were determined using the stepwise regression method. The three distances from the shoulder were calculated for the 18 tested postures using trigonometry. The average shoulder height was used as well as the average reach distance from the subject group. The arm reach data collected from each subject, combined with the other positional variables in the current study, allowed for the conversion of the postures into H, V, and L. For both L and H, knowing both the reach distance and angle (0°, 45°, 90°) allowed the researcher to calculate distance from shoulder to handle. For V, the acromio-clavicular joint was 33.5 cm above the iliac crest and 18cm below the top of the head. These distances were used to convert values to three dimensional distances. Please refer to Appendix D for the measurements. This enabled the measurements from the current study to be converted into the distance, in three dimensions, from the shoulder (0,0,0) to the exertion location at the hand. For some subjects, there were postures that were not possible to attain at both high and low heights with a 40% reach distance. For these postures, the angle and height conditions were maintained but the reach distance was decreased, therefore bringing the subject closer in horizontal distance to the handle. For these instances, the actual reach distances were used to generate the equations.

For exertions above the shoulder, the vertical height of the hand (V) was used in five of six equations. For exertions below the shoulder, however, V was only used in one equation. In equations both above and below the shoulder, the lateral location of the hand (L) was used in five of six equations. Another variable shown to be rather important was L^2 which was used in nine of 12 equations. Figure 42 illustrates the regression results for all six directions. The mean r^2 value was 94.6% and the greatest RMS % Error was only 5.4%.

Table 13: The regression force equations developed for each of the six exertion directions. The first eleven lines for each equation represent the intercept and coefficients for significant variables. Equation statistics are shown below the coefficients.

	Direction	Push	Pull	Up	Down	Medial	Lateral
Above Shoulder	Intercept	94.21	99.16	108.12	73.29	113.18	70.98
	H		0.437193		0.946123		0.898778
	V	-0.493945	-0.902585	-0.773648	6.676061	-1.253165	
	L	-0.517902	-1.028711	-0.624148		-1.012638	-1.203535
	H^2	0.016692	0.010101	-0.016887		-0.017139	-0.024440
	V^2						
	L^2	-0.007045		-0.008403	0.016816	0.031123	0.036376
	H*L				0.014541		-0.009881
	H*V		-0.003787		-0.130010	0.005651	-0.009919
	L*V		0.018885	0.036479	-0.126666		0.009587
	F	78.00	1533.39	14.85	6.46	278.75	162.68
	Prob	>0.0001	>0.0001	>0.01	>0.01	>0.0001	>0.0001
	RMS Error	4.46	0.93	5.21	12.62	1.73	1.28
	RMS %Error	5.2%	1.1%	6.6%	10.3%	1.9%	1.8%
	R^2	97.8%	99.9%	92.5%	88.6%	99.6%	99.6%
Below Shoulder	Intercept	91.47	92.59	114.87	89.83	113.29	64.74
	H	0.435094	1.020935				
	V						0.189073
	L	-0.785586	-0.938903	-0.855078	-1.565837	-1.128010	
	H^2	0.007749		-0.022884	0.016677	-0.017028	
	V^2		-0.007369			-0.034577	
	L^2			-0.008167	0.048320	0.034187	0.013221
	H*L			0.010173	0.017685		-0.013709
	H*V			-0.009329		-0.009565	
	L*V	0.010098			-0.007323	-0.034763	
	F	51.36	50.32	109.20	26.11	48.63	7.00
	Prob	>0.0001	>0.0001	>0.0001	>0.001	>0.001	>0.05
	RMS Error	5.10	7.19	2.84	5.49	3.92	7.48
	RMS %Error	5.8%	8.0%	3.2%	5.6%	4.2%	11.4%
	R^2	96.7%	95.0%	98.9%	95.6%	98.3%	72.4%
Mean RMS %Error		5.5%	4.5%	4.9%	8.0%	3.0%	6.6%
Mean R^2		97.3%	97.5%	95.7%	92.1%	98.9%	86.0%

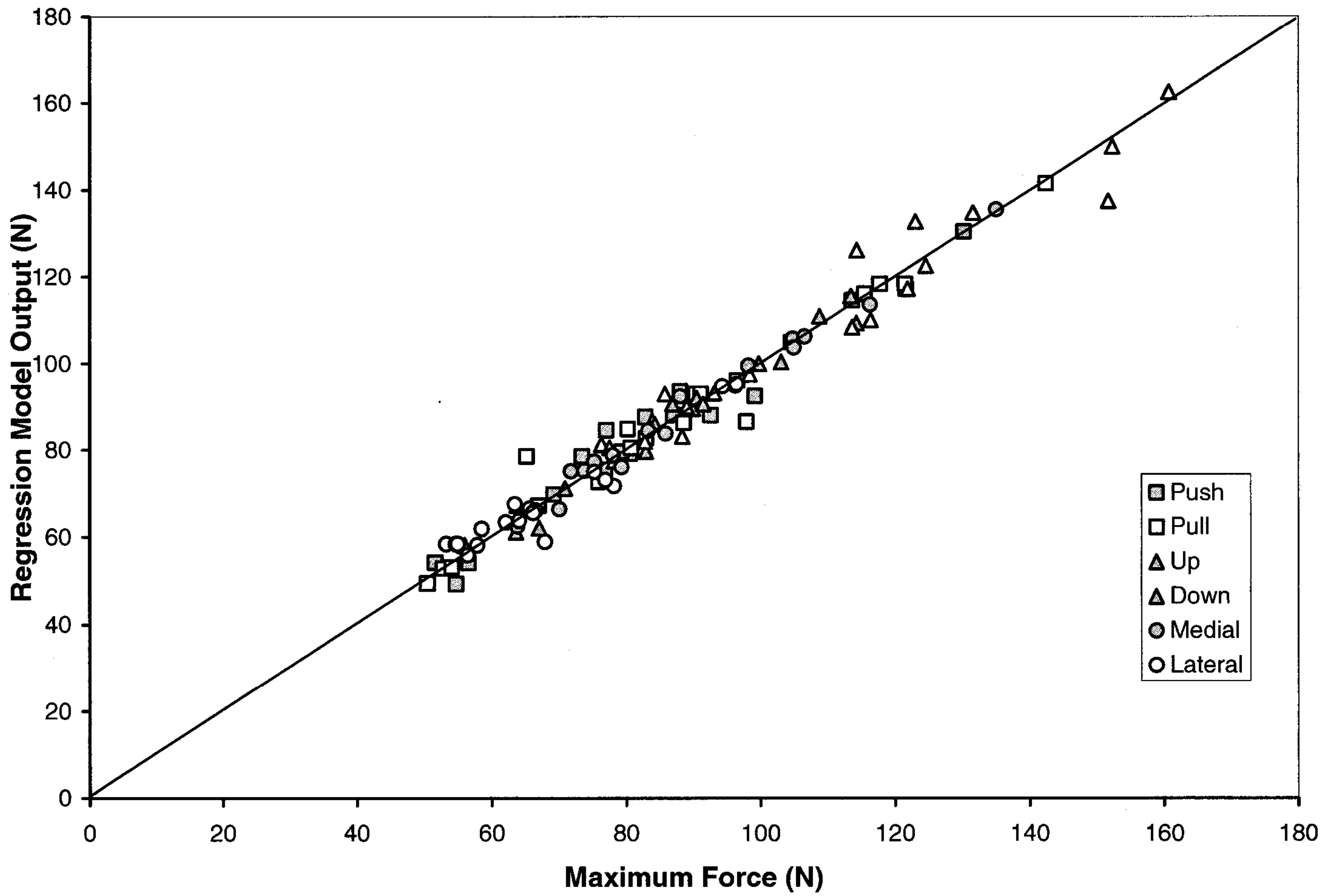

Figure 42: Comparison between force values collected in current study and those generated by the regression model. A trend-line is included depicting the linear relationship of the data.

Chapter 5: DISCUSSION

The current study was designed to examine the relationship between strength, EMG and posture as used in various tasks. This was accomplished by way of biomechanical methodologies. A group of 29 female subjects performed a set number of exertions in 20 different arm and shoulder postures. The independent variables of the study were height of exertion (waist, shoulder, and head height), angle of exertion (0°, 45°, and 90° to the para-sagittal plane), percentage of full reach (40% and 80%), and direction of exertion (push, pull, push up, push down, exert lateral, and exert medial). The variables tested were split into two categories: 1: Kinetic, or the amplitude of the force exerted by the subject on the load cell; 2: EMG, using surface EMG to record the percentage of MVC for the BB, TB, DA, DL, and TR muscles during the tasks at the point of peak exertion. The published literature on this topic has not looked at the same number of postures, directions, or both in tandem.

5.1 Exertion Direction

5.1.1 Push Forward

Height: For the push direction, it was seen that the highest strength values occurred in the exertions at medium height (H_M). This may be the result of body posture and corresponds with the findings of studies conducted comparing force and upper limb postures (Haslegrave *et al.*, 1997; Roman-Liu and Tokarski, 2005). These studies found that push forward exertions at shoulder height produced the greatest force values of all posture tested. When performing exertions at the shoulder height, the dominant muscles are the anterior deltoid, causing arm flexion, and the triceps brachii, causing forearm extension. At H_H, the arm is in a non-neutral posture, or overhead, which has been shown to potentially increase muscular fatigue of the shoulder muscles (Haslegrave *et al.*, 1997). Furthermore, muscle fatigue can be assumed to be an indicator of injury risk (Nussbaum *et al.*, 2001). Many studies have psychophysical methods, related to a subject's ability to accurately predict a safe level of force (Ciriello and Snook, 1999; Potvin *et al.*, 2000; Snook, 1978). Flatow, Soslowsky and Ticker (1994) state that work in overhead positions is potentially harmful to structures of the shoulder girdle. A potential contributing factor to why subjects exerted less force at H_H, may be the inhibition of the muscle groups. Studies have shown that inhibition is sometimes used as a mechanism to protect the muscles from soft tissue overexertion injuries by way of incomplete activation (Westing *et al.*, 1991; Young and Stokes, 1986).

Exertions at H_L were also found to be lower than H_M. This posture is also non-neutral, however muscular inhibition is unlikely in this case as it falls below the 60-120° range of shoulder elevation angle where tendon impingement in the shoulder is likely to occur (Flatow *et al.*, 1994). What is more likely is that, at H_M, the arm muscles like triceps brachii (TB), along with the other extensors, are able to aid in contraction whereas at H_L the extensor muscle group is very limited due to the lower posture of the arm. This was substantiated by results of the current study where the TB exhibited very low EMG_{PK} at H_L when compared to exertions at the other two heights. These results are similar to those found by Roman-Liu and Tokarski (2005) who showed that, for push forces, as the angle of the upper arm decreased (moving in the sagittal plane about the medio-lateral axis through the shoulder) the force also decreased. Force generation increased as the flexion angle of the arm increased up to approximately 90° in sagittal plane (where 0° refers to the arm being at the side in the same axis and plane). The results of this study showed that the highest pushing forces occurred with an arm flexion angle identical to the angle at H_M from the current study, where the highest forces were observed across all heights.

The anterior deltoid (DA) was found to be the dominant muscle in this direction. Exertions at H_L exhibited the highest activation at both reaches and all three angles. When the subject must exert a force at a low height, the DA is one of the major muscles contributing to forward push. According to Tortora (2005), the anterior fibers of the deltoid flex and medially rotate the arm at the shoulder joint. At H_M, the DA exhibits high EMG_{PK} for the same flexion and medial rotation actions. At H_H the DA is still helping to flex the shoulder joint to maintain the posture.

Angle: There was a clear downward trend observed in push force as the horizontal arm angle of exertion increased from 0 to 90°. Biomechanical properties of the body have a large impact on this. At 0° and shoulder height, there is no moment about the shoulder produced when pushing. The force is in-line with the locked arm and the subject is able to use both upper arm and shoulder muscles efficiently to generate a maximal force. As the angle increases, so to does the moment arm. At 45°, there is a moment arm created, which is the perpendicular distance from the line of action at the hand to the axis of rotation at the shoulder. At 90°, there is a greater moment arm created. As the perpendicular distance from the line of action to the axis of rotation increases, the amount of linear force the subject is able to generate decreases.

The muscle groups utilized varied greatly from 0° to 90°. At 0°, the shoulder muscles, and upper arm muscles were used together to generate a maximal exertion. At 90°, the pectoralis muscles would be the main muscles used. They were not measured but they would play an important role in medially rotating the arm at the shoulder joint (Tortora, 2005). The upper extremity muscles (BB and TB) are not able to aid in the force production at 90° due to the fact that the contraction is neither an arm flexion nor extension. This is also the case at 45° but to a lesser extent. These results are consistent with those found by Roman-Liu and Tokarski (2005) where it was observed that, as humeral rotation angle increased, the amount of force production decreased in push forces.

As stated above, the dominant muscle in this direction was the DA. It was found that, as angle increased to 90°, the activation decreased. While the moment arms are the same, the muscle involvement is not. As stated by Tortora (2005), the DA flexes and medially rotates the arm at the shoulder joint. This means that at 0°, the activation would be expected to be the highest because it is an an arm flexion exertion. The reverse is seen at 90°, where the DA exhibits the lowest activation. This is a result of the lateral horizontal rotation about the shoulder joint. In this posture the arm is not in flexion and therefore, the DA is less effective during this contraction.

Reach: There was little impact observed in push force as reach distance changed. There was a slight increase in force capability as the distance decreased from 80% (R_2) to 40% (R_1). The reach variable interacted with both height and angle separately and together. There was very little change between the EMG activation for the DA (dominant muscle) as well across reach distances. What was found when analyzing the significant differences was that the other variables, height and angle, had much more of an impact on activation.

5.1.2 Pull Backward

Pull backward forces displayed almost identical effects to those in the push forward direction. There were, however, different muscle effects observed for this direction. The dominant muscle measured in this direction, across almost all conditions, was the lateral deltoid (DL). There are other unmonitored muscles that would have contributed to the force generation, such as the, posterior deltoid, latissimus dorsi and the rotator cuff muscles. The DL is responsible for abduction of the arm at the shoulder joint (Tortora, 2005).

Height: The highest activation for DL occurred at H_H and decreased as the height decreased. DL did not exhibit the same level of activation at H_L which was likely a result of the arm orientation, as explained above. In the higher position, subjects often laterally rotated their humerus (moving their elbow laterally and superiorly) to get their arm in a more advantageous position to exert the force. At H_L, the subjects were not able to rotate their arm the same way as the exertion was so low that the posture was not readily modifiable. In the H_L exertions, the latissimus dorsi would be the dominant muscle as it is responsible for drawing the arm inferiorly and posteriorly (Tortora, 2005).

Angle: DL exhibited the highest activation at 45°. This was not unexpected and may be largely due to arm orientation. At 45°, in order to pull straight backward (with greater than 95° of the resultant in the backward direction) subjects flexed their wrists and laterally rotated their humerus, dropping their elbow. This action resulted in the increased activation of the DL during the effort. At 0°, the DL did not display the same, high level of activation. High levels of activation were observed in the BB at both H_H

and H_M and in the TB at H_L at 0°. At 0°, the action was a forearm flexion, which is what the BB is responsible for (Tortora, 2005).

Reach: There was a slight increase noted in activation as reach distance increased from R_1 to R_2. This may be due to the increase in the moment arm. An increased moment arm can lead to a decrease in the force production. To produce a maximum amount of force the activation levels may increase for the maximum exertions. In the current study, when reach was combined with angle, an increase in activation was seen at both reach distances as angle increased. The explanation for this is similar to that of the angle effect above. As the angle increased to 90°, the larger reach enabled (along with the drop in elbow height and humeral rotation) the DL to perform the abduction action at the shoulder joint.

5.1.3 Push Up

Height: The greatest force values were observed at H_L and the force decreased as the height increased, which corresponds with results from Roman-Liu and Tokarski (2005). The reason why the force is greatest at H_L is due to muscle involvement. When the hand was below the waist, the BB and DA are the muscles that would dominate these exertions, as was seen in the EMG_{PK} of the current study. For a push up exertion, when the hand is at H_L, the action of the BB is shoulder and elbow flexion. This is opposite to the situation at H_H where, when attempting to exert upwards, the action is not a forearm flexion, but a forearm extension exertion at the elbow. Therefore, the BB does not provide the same level of activation when the hand is higher and therefore the force is lower. There was not a large difference in force exerted between H_H and H_M observed in the study.

The DA was observed to exhibit the highest activation across almost all conditions. For the DA, the highest activity occurred at H_H, across all angles and both reaches. The DA's main action is to flex and medially rotate the arm at the shoulder joint (Tortora, 2005). The higher DA activity at H_H is due to the arm flexion at this height. When examining activation at the three heights, BB exhibited the least activity at H_H and increased as height decreased. DA was lower at H_L and H_M because less arm flexion, but more forearm flexion, is required at those heights. The muscle with the highest activation at H_L was the BB. This is not unexpected and was addressed above. At H_H, the arm flexion motion requires DA and the forearm extension motion requires TB to generate maximal force in the upward direction. It was found that for the TB, the highest activation for this muscle occurred at H_H.

Angle: There was a small decrease observed in push up force as angle increased. This decrease can be attributed to the muscle groups used and the optimal positions for those exertions. As the shoulder undergoes rotation in the horizontal plane, there is a change in the muscle groups most involved in the contraction. At 0°, the full deltoid muscle can aid in elevation, while the posterior thoracic muscles (TR, levator scapulae, rhomboid major, rhomboid minor) stabilize the scapula during the elevation (Tortora, 2005). At 90°, the exertion is no longer an arm flexion which is what the DA is responsible for. With the arm 90° abducted the DL, which is responsible for abduction, becomes one of the main muscles acting in this posture. The other muscles involved in the exertions at 90° change as well as the posture changes. The muscles involved at the different heights and the subsequent forces produced, were addressed in the above section.

For the EMG, there was a downward trend observed in DA as the horizontal angle of the arm increased from 0° (in sagittal shoulder plane) to 90° (in frontal plane). This finding is not unexpected as the DL is responsible for the abduction required to exert forces upwards. The decrease in activation corresponds to a decrease in the force produced. This corresponds with a study by Roman-Liu and Tokarski (2005), where that, at a horizontal arm angle of 90°, at shoulder height (H_M) they recorded their lowest upward forces. Force was observed to increase as the angle decreased to 0° (sagittal shoulder plane). Stobbe (1982) only tested subjects in one posture, with the upper arm at 90° so comparison between studies is not possible.

Reach: There was a clear decrease in push up force as reach distance increased. Subjects were able to exert higher forces at R_1 than they were able to at R_2. This may occur because as the moment arm decreases the same muscle moment is able to elicit a greater output force (Chaffin *et al.*, 1999). The BB was very active at H_L, having a higher force production owing to the flexion motion of the forearm. At H_L, the exertion is a flexion motion where it is extension at H_H and a combination of both at H_M. These findings also support those of Anton et al. (2001) who conducted a study on overhead working positions and included reach as a variable. It was found that a closer reach was more advantageous when working overhead. Another study, by Haslegrave, Tracy, and Corelett (1997) had similar findings. They found that subjects were able to exert greater vertical forces as the overhead reach distance decreased.

When comparing the EMG at both reach distances, very little change was observed. Reach interacted with both height and angle separately, but neither elicited a great discrepancy when moving from R_1 to R_2. At R_1 and R_2, the highest activation occurred at H_H and the lowest at H_L. For angle and reach, the only difference in activation was observed at 0°, where R_2 was significantly greater.

5.1.4 Push Down

Height: The height effects, for exertions in the push down direction, were quite different than those of the push up direction. The action of TB is to extend the elbow and extend the shoulder (Tortora, 2005). For the exertions in the higher locations, the main action of the TB is shoulder extension. As the height of the exertion decreases, the action becomes less of a shoulder extension and more of an elbow extension, as there is less and less distance for the arm to extend. The greatest push down forces, were exhibited at H_H. In the push down direction, the H_M is the middle force whereas H_L produced the lowest force. At H_H when pushing down, the arm is extending and the forearm is flexing. Where BB causes forearm flexion, TB causes arm extension. The high forces at H_H are due to the combination of these two muscles working together. At H_L, however, the BB is not able to aid in the exertion as, in this posture, it is an extension not a flexion motion. The recording of the highest values at H_H corresponds with both Stobbe's (1982), work and prior work by Clark (1966) that found that the optimal vertical shoulder angle is approximately 100°. If Stobbe's measuring procedures are used to compare angles, the current study used a vertical shoulder angle of approximately 85-90°. The TB muscle would be the dominant muscle for exertions at all heights and angles as was evidenced by the EMG results from the current study.

Angle: The same trend in force amplitude was observed for push down forces as was for push, pull and push up forces. As the angle increased, push down forces decreased. At 90°, the push down action is adduction. The main muscles involved in adduction are pectoralis major and latissimus dorsi, neither of which was measured for the current study. The BB and TB aid in the flexion or extension of the arm at the shoulder joint. Therefore, the TB can aid in the push down force at 0° and somewhat at 45° along with pectoralis major and latissimus dorsi (Tortora, 2005). Little research has been found that discusses push down forces in varying angles but one study showed that, as the horizontal angle deviated from 0°, the amount of force production did decrease (Haslegrave *et al.*, 1997). This corresponds with the results of the current study.

Reach: As can be expected, the downwards force produced is greatly affected by the reach distance. There are two factors which may have an impact on the force results for reach distance. The first is that, as the moment arm increase (increased reach) the force values will decrease for a given moment (Chaffin *et al.*, 1999). This was not the case, however, as the force was found to increase with reach. The second factor is muscle orientation. At some reach distance, or elbow angle, the force production capability begins to decrease again. Strength data collected from subjects in different arm/forearm postures consistently show that the optimal elbow angle for strength (when pushing down) is between approximately 70° and 100° (Clark, 1966; Elkins et al., 1951; Schanne, 1972; Singh and Karpovich, 1968; Williams and Stutzman, 1959). After 110°, strength begins to decrease. At R_1 the forearm angle is less than the 70° listed above, at H_H and H_M, whereas, at R_2 the forearm angle falls within the 70-100° degree range. This would explain why at R_1 in the current study, force production was lower than at R_2.

5.1.5 Medial

Height: The highest forces were recorded at H_M. The muscles responsible for medial flexion of the arm include the BB, pectoralis major, and subscapularis (Tortora, 2005). A possible reason for this is greater muscular involvement at H_M than at other heights. It is likely that the pectoralis major, at this location, is able to exert the greatest amount of force. Many subjects abducted and medially rotated their arm by swinging their elbow away from their side. This allowed them to use the arm musculature, such as the BB. At H_H and H_L, the subjects were not as able to move their arms into an advantageous posture and the BB could not contribute to the exertion like it could at shoulder height.

It appeared that the dominant muscle at H_L and H_M was the BB and the dominant muscle at H_H was DA. BB exhibited the highest activation at H_M and the lowest at H_L. This activation level, at H_L, while the lowest for the BB, was still greater than the other measured muscles at this height. For the BB, there was little change in the activation at H_L due to the inability to alter arm position at this testing height. Consequently, the advantage that subjects had at H_M, they did not have at the other heights, especially H_L.

The DA muscle showed a large increase in activation as height of exertion increased, with the highest being at H_H. The DA is responsible for flexion and medial rotation of the arm (Tortora, 2005). The large increase with height was expected, as the shoulder flexes more with each increase in height. In addition, this medial direction is aided by the DA by way of medial rotation.

Angle: The greatest medial force was observed at 90°. This finding was expected as, in this posture, there was no moment arm and the force is in direct line with the arm (Chaffin *et al.*, 1999). The subject can use the arm musculature, such as the BB, as well as the trunk musculature, such as the serratus anterior, TR, rhomboid major and rhomboid minor, to both aid and stabilize the glenohumeral joint and scapula and thereby generating a large amount of force (Tortora, 2005).

There was an increase in BB activation from 0° to 45° but not much change from 45° to 90°. The initial increase may be due to the inability for the BB to aid in the medial force generation at 0°, as the arm is moving medially and the BB does not contribute to that action. However, as the arm moves further laterally the BB is more able to aid in the exertion due to the arm posture and the bend at the elbow.

There was a downward trend observed in DA activation as the angle increased. This can be explained using the above reasons as well. As the angle increases, the DA is effectively prevented from participating due to the orientation of the arm. The arm, at 90°, exerts a force along the medio-lateral axis through the shoulder. There is no moment arm and the force is in line with the arm. The DA cannot contribute other than stabilization of the shoulder joint.

Reach: As the reach distance increases at both H_H and H_M, the force amplitude was observed to decrease slightly, further confirming that, in most cases, that force decreases as the moment arm increases (Chaffin *et al.*, 1999). The opposite was found at H_L, where forces at R_1 were found to be lower than at R_2. A potential factor is the awkwardness of the posture when at R_1. In this posture, the arm is so close to the body and angle of the forearm is below approximately 45°. This angle is well below the flexion angle of 90-110° used by Stobbe (1982). At R_2 the forearm angle is approximately 90° which falls within the recommended range where subjects have been shown to exert the maximum amount of force (Clark, 1966; Elkins et al., 1951; Schanne, 1972; Singh and Karpovich, 1968; Williams and Stutzman, 1959). Greater activation was observed at R_1 than at R_2 across all conditions for BB. DA activation remained almost unchanged between R_1 and R_2. The change for BB would support the theory that as the moment arm increases, the force decreases (Chaffin *et al.*, 1999).

5.1.6 Lateral

The forces exerted in the lateral direction were, on average lower than the forces exerted in all other directions. The TB and DL were found to be the dominant muscles in the lateral direction.

Height: There was little difference in force production exhibited across the different heights, but H_M resulted in the highest forces. These results correspond with those of Haslegrave *et al.* (1997) who found that all of the exertions tested in the lateral direction at shoulder height were greater than all exertions above shoulder height. While their study did not examine similar postures it did examine exertions in the lateral direction at shoulder and at or above head height. No exertions were tested below shoulder height, so comparison with H_L exertions is not possible.

Angle: The greatest forces were recorded at 90°. This was the expected finding as the forces are in direct line with the arm and with no moment arm the subject should be able to produce more force (Chaffin *et al.*, 1999). Forces recorded at both 0° and 45° were found to be very similar.

TB was found to be the most active at 45°. TB is responsible for extension of the arm and forearm and the lateral exertion is an extension at the shoulder, especially at 45° (Tortora, 2005). There was, however, minimal change between exertions across all three angles. For DL, exertions at 0° were found to be significantly greater than those at the other angles. DL is responsible for abducting the arm at the shoulder joint, which would help the arm move more laterally as it must for this exertion (Tortora, 2005). It must be assumed that there were other muscles (latissiums dorsi, infraspinatus, teres major and minor) that were not measured for the current study that contributed to these exertions.

Reach: There was little difference in the force production between the two reach distances. R_2 was found to be slightly higher than R_1. This reach distance has a larger moment arm however, which has been found to lead to a force decrease (Chaffin *et al.*, 1999). R_1 may be lower due to the small arm-forearm angle. For forearm extension at the elbow, the angle in which Stobbe (1982) used to test his subjects was 70°. The range found where subjects can exert maximum force values was approximately 70-100° (Clark, 1966; Elkins et al., 1951; Schanne, 1972; Singh and Karpovich, 1968). In a study performed by Roman-Liu and Tokarski (2005) arm-forearm angle was measured, and it was found that, for all exertions except pronation, the lower the angle the lower the force. They did not measure lateral movements, however, but their findings suggest that between 0-120° (approximately), as the arm-forearm angle increased, so did the force production.

For TB, it was found that all three variables interacted together. TB was found to be the dominant muscle at H_H, which was unexpected. When interacting with angle, however, it can be seen that at 45° and H_H, the TB is most active. This finding is in line with the actions for TB which, in this case, is arm extension. Similar findings can be seen at both reach distances.

For DL, only two of the variables interacted, height and reach. For R_1, exertions at H_L exhibited the greatest activation. Reasons for this relationship are unclear. For R_2, exertions at H_M had the highest activation. Exertions at shoulder height were found to be higher than all other heights for exertions in the lateral direction in a study by Haslegrave *et al.* (1997).

5.1.7 Exertions at -20°

The forces produced were found to be significantly different at -20°, compared to the corresponding exertions at 0°, in four of the six directions.

Push Forward and Pull Backward: Higher forces were recorded at 0° where the arm is in-line with the shoulder and there is no moment arm caused by the hand position. According to previous research, the smaller the moment arm the more force the subject is able to produce (Chaffin *et al.*, 1999).

Medial and Lateral: Unlike the pushing and pulling directions, in this direction, exertions at -20° produced more force than those at 0° at both H_H and H_L. In this case, the exertions at -20° have a slightly smaller moment arm than those at 0°. This may be why there was more force with the hand at -20° (Chaffin *et al.*, 1999). This was the case at both high and low heights. According to research done by Roman-Liu and Tokarski (2005), in the directions they tested, the lower the horizontal arm angle the greater the force.

5.1.8 Age

Age was used in the study as a between variables factor for the repeated measures ANOVA. The results, however, were collapsed across age because the current study was attempting to look at population means. Out of a possible 288 possible maing or interactation effects of age, only 10 (3.5%) were found to be significant and all were either two or three way interactions.

5.2 Regression Model

The regression equations were found to be very accurate. There was a mean R^2 of 94.6% and RMS %Error of only 5.4%. For each direction, two regression equations were needed to better fit the data from the current study. One equation was developed for exertions at and above shoulder height and a second equation was developed for exertions at and below shoulder height. Overall, there were only three main variables used to accurately predict strength data at the hand. The three variables were the horizontal, lateral and vertical distance from the shoulder joint to the exertion location (at the hand). There were an additional 6 variables created from these three variables (H^2, V^2, L^2, HL, HV, LV). For strength prediction in a desired direction, the vertical height relative to the shoulder was important to ensure that the correct equation is used.

When examining the specific variables used in the equations, certain trends can be noticed. For the exertions at and above shoulder height, the vertical height, lateral distance, square of the lateral distance, and the square of the horizontal distance were used in five of six equations. For exertions at and below shoulder height, only the lateral distance was found to be used in five of six equations. In contrast, the vertical distance was only used in one equation and the horizontal distance was only used in two of the equations. The square of the horizontal distance and the square of the lateral distance were used in four of six equations. The variables used in the equations, illustrates which variables explained most of the variance in strength. The vertical distance from the shoulder, for example, was much more important when the exertion is above the shoulder than below. This may be because there is a much greater strength change as height increases when above the shoulder. The lateral distance from the shoulder, on the other hand, was found to be very important in exertions at all heights. The fact that it is used in 10 of 12 equations, suggests that the lateral distance is highly correlated with strength no matter the height.

In addition, the subjects used in the current study were representative of the female working population. There were 10 subjects in each age group between 20 and

40, and nine between 40 and 55, used to represent all age groups. This ensures that these equations can be applied to the North American working population with the results being transferable.

Finally, there was not a validation performed using a sub-sample of subjects from this study. The equations are not to be used for individuals but for whole populations. Furthermore, it was the intent to put as much data as possible into the generation of the equations when performing the stepwise regression.

5.3 Hypothesis Revisited

1. *Strength data will show a statistically significant interaction ($p<0.05$) between angle and direction. Post hoc analysis of these variables will show the highest acceptable limit will be displayed in the sagittal shoulder plane (0°) during pushing. This will be greater than all other directions and angles.*

This statement was made prior to modifications of the methods. Directions and angle were not compared against one another within the statistical analysis. Each variable was analyzed within a direction to determine the results for that specific direction. Upon completion of the study, it was found that of the 18 possible (excluding exertions at -20°) combinations of angle and direction, there were three combinations that exceeded pushing at 0°. They were 1) pulling at 0°, 2) pushing down at 0° and 3) pushing down at 45°. The pulling condition was found to be 5% greater than the pushing condition. Push down at 0° was found to be 8% greater and finally push down at 45° was found to be 1% greater.

2. *Force data will show a statistically significant interaction ($p<0.05$) between reach and height. Further post hoc analysis will show that 80% reach will have*

greater strength than 40% reach distance and that the greatest acceptable levels will be in medium height.

Within each direction, there was a statistically significant interaction between reach and height. This interaction occurred within each direction. The second statement was found to be both true and false. Exertions at 80% reach were found to be greater than those at 40% reach in four of the six directions. Exertions in the push direction and the push up direction found the opposite, that 40% reach exertions were greater than 80% reach exertions. For the push direction, the 40% reach exertions were only 0.4% greater than 80% reach exertions. For the push up direction, the 40% reach exertions were found to be 30% greater than the 80% reach exertions.

3. *It will be possible to develop multiple regression equations to allow for the accurate prediction of maximal hand forces based on inputs of height, reach and arm angle.*

A regression was developed for all 6 exertion directions. The regression equation developed resulted in r^2 values ranging from 86.0% (lateral) to 98.9% (medial) and RMS errors ranging from 8.0% (push down) to 3.0% (medial). The equations use the inputs of height, reach and horizontal arm angle. They must be converted into a three dimensional distance (x,y,z) from the shoulder joint (0,0,0). These values can then be used in the predictive equation to produce the mean of maximum forces the population is capable of exerting.

5.4 Reliability

Subject reliability was measured using a repeated condition in both testing sessions. Subjects pulled backward at H_M, 0°, and R_2 for two trials. For the force measurements, there was a correlation of r=0.8, r^2 of 65% and RMS error of 23% found within subjects, between the testing sessions. This shows that subjects were relatively consistent between testing sessions in their ability to produce a similar maximum force. Of the two trials which subjects performed in each posture, the maximum trial was taken for analysis purposes. The trials were compared however, and found to be very similar in most cases.

5.5 Limitations and Assumptions

In the current study, there were some limitations and assumptions for the execution of the study. The subjects used were not skilled or trained workers, and previous relevant work experience was not a requirement. The subjects were volunteers, selected to fill three separate age groups. The study provided feedback to the subject so that they could learn to exert the force mainly in the intended direction. The exertion had to reach a desired level of accuracy prior to acceptance of the trail. If the resultant force did not achieve the desired level, feedback was provided to the subject to aid in the production of a force resultant in the intended direction. The subjects were able to learn from their mistakes and retry the exertion.

Another potential limitation was the testing setting and apparatus. The study was set up to mimic exertions that people would have to perform for their work tasks, specifically on some sort of industrial assembly work. The subjects performed maximal isometric exertions against a padded handle. If subjects were performing a similar task in their workplace, the exertion would likely not be static but dynamic. Mital and Kumar (1998a) describe a form of static testing called 'Simulated job static strengths.' It is defined as static strengths measured while body posture aspects of the job are replicated. There are however some limitations with testing a dynamic action using static methodology. There is no limb or object movement in static contraction so the inertial force(s) effect cannot be accounted for. According to Mital and Kumar, this leads to the underestimation of musculoskeletal joint loading during what is usually a dynamic task. In addition, where an exertion may be required over a specified range of motion, statics only measure strength in one posture. This does not, however, indicate that static muscle testing is not valid. Many researchers have used static methodologies to better understand dynamic muscles strengths. Researchers such as Anton (2001), who had subjects simulate overhead drilling tasks. Subjects used body positions and angles to simulate an actual drilling task but the exertion was static. Haslegrave, Tracy and Corlett (1997) performed a study examining the isometric strength of subjects in awkward postures, in order to relate their abilities in working situations. Other researchers who studied static tasks testing, and then related them to dynamic tasks, include: Roman-Liu and Tokarski (2005), Das and Wang (2004), Keyserling, Herrin and Chaffin (1980), and Kumar (1991) among others.

Another potential limitation to the study was the impact of fatigue on the exertion strengths. There were two data collection sessions in which the subject performed half of the total testing exertions. There was at least one rest day between testing sessions in all cases. In each session, the subject exerted two trials, in each of the six directions, in 10 postures. Subjects were, however, given breaks between postures to prevent fatigue from affecting the maximal forces. Muscle fatigue was not monitored in the current study. The assumption was made that enough break time was provided during the testing session to ensure maximal contractions were possible. There has been a slower onset of fatigue found in females during intermittent work. In addition, the anterior and middle deltoid were found to be the most susceptible to fatigue (Nussbaum *et al.*, 2001). It has been reported that MVC's performed as often as once per minute had no effect on exertion capacity after 30 repetitions (Lewis and Fulco, 1998).

Finally, the bias collected for each height and reach condition was not removed from the final peak forces. This means that, for all postures when the torso is not vertical, the bias will have to be removed for exertions in the vertical direction. The 4 equations for the exertions in the vertical directions (push up and push down) can only be used for exertions where the trunk is upright.

5.6 Recommended Acceptable Limits

According to previous research, if a manual handling job task is acceptable to less than 75% of the working population then a worker is three times more susceptible to injury (Snook, 1978). This 75 percentile level has been accepted as the optimal design level in order to prevent as many work related musculoskeletal disorders as possible while keeping costs acceptable. In Snook and Ciriello's research (1991) they used a correction factor to apply their data to all different postures and situations. They did not test every posture with enough subjects to get adequate statistics to determine the exact 75^{th} percentile for each posture. As detailed in Table 1 (Snook and Ciriello, 1991) of their paper, they used nine criterion tasks and applied these correction factors to all other postures in the surrounding tasks.

For the current study, using the same methods as above, an average coefficient of variation (CV) was calculated by taking the mean of the CV's from all six directions. The CV's ranged from 25% (push up) to 32% (push forward) and the mean CV was approximately 29%. Using this figure, the correction factor to make each effort acceptable to 75% of the female population is 0.808. In other words, 80.8% of the average strength would be possible for three quarters of females.

Chapter 6: CONCLUSIONS

6 Conclusions

The data collected from the current study showed that, as the physical location of the hand changed, the maximum force amplitude also changed. For height, in four of the six directions, the highest forces were recorded at medium height (H_M) with the exception being in the push up and push down directions. For angle, it was found that, for four of the six directions, as angle increased, force decreased. The two exceptions were when forces were applied in the medial and lateral directions. For reach, in four of the six directions, force decreased as reach distance increased. The exceptions were push forward and push up. Interactions were found between variables in all directions. There were four three way interactions found in the six directions. This shows that inter-related nature of the variables used in this study.

The EMG data showed that there were eight three way interactions between height, angle and reach. In one direction or another, each monitored muscle exhibited a significant three way interaction. There were also many two way interactions and a few main effects found to be significant.

The regression equations developed showed that the values obtained in the study could be accurately predicted using the input variables of height, angle and reach and/or some combination of them. Furthermore, these equations can then be used to predict the maximum acceptable forces for females when exerting forces in a given location and direction.

6.1 Implications for Industry

Many tasks within industry require workers to exert a hand force in a given location and direction. These exertions can often involve awkward postures of the arm. Prior to this study, there were few studies that examined the maximum acceptable hand forces in such a wide range of postures. Furthermore, the current tools used by industry to determine maximal upper extremity forces are based on a study that does not have enough information to accurately predict force capabilities (Stobbe, 1982). While the data from that study are accurate and valuable, measurements were not taken at the hand and only six postures were tested. This study used 18 postures to develop regression equations to accurately predict maximum capable forces. These forces were recorded at the hand and no postured constraints were used. This allowed the subjects to adopt whatever posture they felt most comfortable in, which duplicates the way a worker would perform the task in a real setting.

The regression equations developed here will allow ergonomists and/or employers to determine what the maximal amount of force a population of females is capable of performing as well as what the 75th percentile female is capable of performing. The current software tools do calculate a value in different postures, however, as previously stated in section 1.1, it is not known at what level of accuracy this occurs or in which postures it is accurate. This is because of the potential errors in the interpretation of the values. Where the strengths were calculated just proximal to the elbow, the software uses it to predict strength at the hand. Knowing this value will enable employers to design for the 75th percentile which has been shown to decrease the prevalence of musculoskeletal injuries. It is also important to note how these equations can be used. The equations are made to be entered into a software package for both job design and job analysis. The software package would have a humanoid model in order to scale population anthropometry. .

6.2 Future Research Directions

Further to the study, comparisons between the current results and those of 3D SSPP in the same postures should be conducted. This would help either validate the current tools or illustrate the differences between 3D SSPP and the empirical data. Future research in this area should also concentrate on the various postures which subjects, or employees, use to perform specific tasks. Having an accurate picture of the postures used to perform tasks would allow for the better prediction of postures humans use to perform tasks as well as the ability to attain certain postures. Postures from a study would show which postures humans employ for exertions in different locations. Some unexpected postures for example, may be used for exertions in locations that are farther away. Once there is a large database developed of these postures, it can be used in the virtual design realm to predict how humans perform jobs and could therefore help improved design.

Currently, many industries are using virtual reality design to eliminate any ergonomics issues prior to the building a physical model. This can be both a cost and time savings to companies wanting to avoid costly delays relating to ergonomics. Having accurate data in virtual reality models is important to ensure that the results are reliable and useful. Furthermore, the postures used to perform tasks are important to help provide a complete understanding of where work tasks are located. This information could also help with the prediction of work methods and timing. In addition the information can help ensure that recommended acceptable limits for both forces and awkward postures are not exceeded.

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APPENDICIES

APPENDIX A

UNIVERSITY OF
WINDSOR

CONSENT TO PARTICIPATE IN RESEARCH

Title of Study: **Investigation of Female Shoulder Strength**

You are asked to participate in a research study conducted by **Chris Freeman and Dr. Jim Potvin,** from the **Department of Kinesiology** at the University of Windsor. The results of which, will contribute to a masters thesis. **This research is sponsored by the Ford Motor Company.**

If you have any questions or concerns about the research, please feel to contact **Chris Freeman:** ***253-3000 ext. 2468*** **or Dr. Jim Potvin***: 253-3000 ext. 2461*

PURPOSE OF THE STUDY

The purpose of this study is to develop regression equations able to predict maximal force exertion at the hand. In evaluation of the current ergonomic tools used by ergonomists, it has been determined that there are deficiencies in the current tools for the upper extremities. This study will use biomechanical methods to evaluate arm strength in various postures.

PROCEDURES

If you volunteer to participate in this study, we would ask you to do the following things:

Participants will stand in front of a subject frame holding a triaxial force transducer. Subjects will then be asked to apply as much force as possible (maximal voluntary contraction or MVC) on a handle attached to a force transducer that is set in various positions. Participants will apply MVCs in the direction indicated by the experimenter.

Each participant will repeat this for a total of six different directions for each position. Each effort will last for 3-5 seconds. Subjects will perform three trials within approximately 2 minutes for each posture. They will be given 5 minutes rest between postures.

Subjects will be tested in 9 postures per session and will return for a total of 2 sessions (for a total of 18 postures + 1 additional posture). Three criterion postures will be determined and subjects will perform MVCs in these postures each of the three sessions.

POTENTIAL RISKS AND DISCOMFORTS

Subjects may experience some muscular fatigue in the shoulder and or upper arm. Subjects will be given adequate rest periods however, and this should help to minimize muscle fatigue.

Should a subject experience abnormal amounts of pain the arm or upper arm, the experiment will be terminated immediately and may complete the testing on another day.

POTENTIAL BENEFITS TO SUBJECTS AND/OR TO SOCIETY

Benefits of participating in the study would be to experience first hand some of the methods and procedures used in conducting ergonomic research. It is likely that a number of the younger subjects will be Kinesiology students, currently learning about strength assessment protocols in there undergraduate and graduate courses.

The results of this study can be used by industrial ergonomists to determine shoulder strength in different positions. This information is invaluable when designing new jobs or rebalancing existing jobs. The results can be directly applied to the design stages of assebmly line and job task design.

PAYMENT FOR PARTICIPATION

Participation in this study is voluntary. Subjects will receive no monetary compensation for participation.

CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission.

Subjects will be identified by alphanumerical code, not by name. Any digital photographs of the subjects will have their face blanked out to ensure that they are not identifyable. All digital files will be stored securly by the researcher. No others will have access to them.

PARTICIPATION AND WITHDRAWAL

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

FEEDBACK OF THE RESULTS OF THIS STUDY TO THE SUBJECTS

Upon completion of the study a summary page will be produced summarizing the findings and industry implications. This summary page will be mailed to each participant.

RIGHTS OF RESEARCH SUBJECTS

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

Research Ethics Coordinator
University of Windsor
Windsor, Ontario
N9B 3P4

Telephone: 519-253-3000, ext. 3916
E-mail: lbunn@uwindsor.ca

SIGNATURE OF RESEARCH SUBJECT/LEGAL REPRESENTATIVE

I understand the information provided for the study **Investigation of Female Shoulder Strength** as described herein. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

____
Name of Subject

______________________________ ______________
Signature of Subject Date

SIGNATURE OF INVESTIGATOR

These are the terms under which I will conduct research.

______________________________ ______________
Signature of Investigator Date

UNIVERSITY OF
WINDSOR

SUBJECTS NEEDED

WHO CAN BE A SUBJECT?

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

HOW LONG WILL IT TAKE?

Over a two week period, each participant will perform the experiment in the Ergonomics Laboratory located in room 207 of the Human Kinetics Building. The total number of hours of participation will be 2 hours over the 2 week period. Each session will last a maximum of 1 hour. Scheduling hours will be flexible. The study will begin November 2005.

WHAT WILL YOU BE DOING?

This biomechanical based study is being conducted to develop the strength values of the shoulder and upper arm. You will be asked to exert an effort at the hand in 6 different directions for each tested posture. You will be required to perform this task in 19 postures used in industry (9 postures per session +1 additional posture).

WHO TO CONTACT?

Chris Freeman
Master's Degree Candidate
Faculty of Human Kinetics,
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Phone: 253-3000 ext.2468

Dr. Jim Potvin
Associate Professor
University of Windsor
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APPENDIX B

UNIVERSITY OF
WINDSOR

Subject Information Sheet

Subject Number	Subject Name

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

Age	Height (m)	Mass (kg)

Handedness	Right
	Left

Have you ever experienced an Upper Extremity Injury?	Yes
	No

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

APPENDIX C

1.1 Push Forward

All were presented in results.

1.2 Pull Backward

All were presented in results.

1.3 Push Up

All were presented in results.

1.4 Push Down

All were presented in results.

1.5 Medial

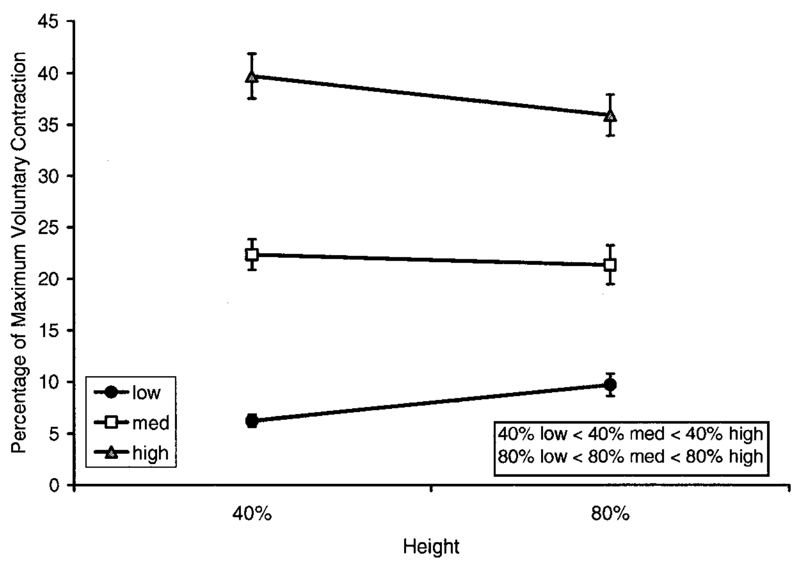

Figure 43: Two-way interaction between height*reach ($p < 0.0001$) for DA. (n=34). Standard error bars are presented. Post hoc results are presented.

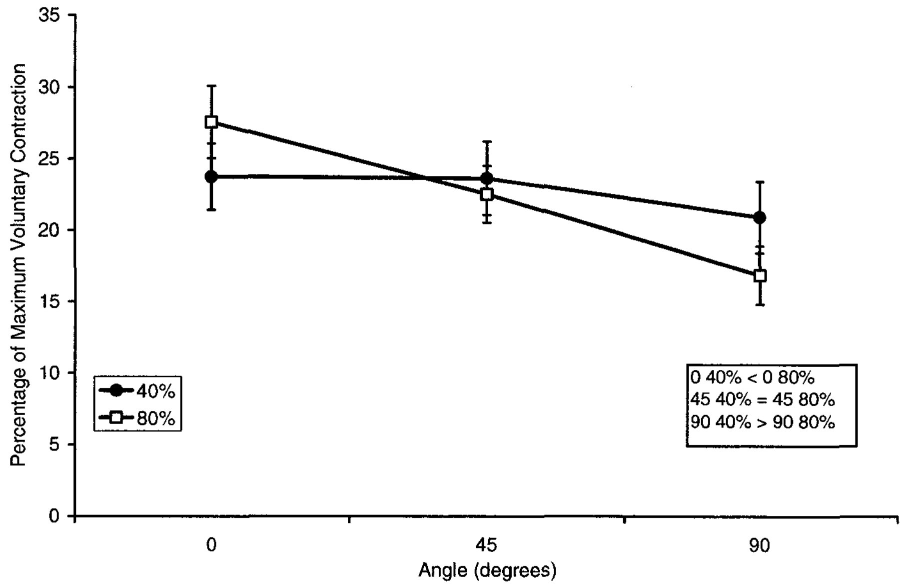

Figure 44: Two-way interaction between angle*reach ($p < 0.01$) for DA. (n=51). Standard error bars are presented. Post hoc results are presented.

1.6 Lateral

All were presented in results.

Table 14: The standard deviations of the means of the all peak activation levels for each muscle for each condition in all six directions.

		Standard Deviations																	
		High (head)						Med (shoulder)						Low (waist)					
		0°		45°		90°		0°		45°		90°		0°		45°		90°	
		80%	40%	80%	40%	80%	40%	80%	40%	80%	40%	80%	40%	80%	40%	80%	40%	80%	40%
Push Forward	BB	6.1	7.1	7.0	5.0	6.9	10.4	7.0	8.4	8.9	13.6	9.2	8.8	11.6	7.3	8.5	13.2	10.3	8.6
	TB	16.9	13.1	7.5	10.2	6.2	11.6	23.4	19.3	10.9	8.1	7.4	7.6	5.9	6.1	5.2	4.9	5.1	5.3
	DA	7.5	9.5	11.0	9.1	10.0	13.0	14.6	11.6	12.7	10.0	9.0	9.1	19.1	14.5	12.5	11.7	12.3	14.1
	DL	5.4	14.8	13.0	10.7	11.6	12.7	6.4	6.9	10.9	10.2	8.9	9.3	6.9	6.2	9.3	8.3	8.4	8.3
	TR	9.3	15.0	7.4	9.4	8.3	11.9	9.5	11.9	7.9	13.4	7.9	12.1	8.2	5.2	6.8	6.5	6.2	7.9
Pull Backward	BB	13.2	13.8	12.1	9.6	9.6	10.6	20.6	21.8	4.4	11.5	5.3	12.5	2.4	2.9	4.4	5.7	3.8	6.8
	TB	7.5	10.2	10.9	11.2	11.3	9.2	9.0	6.7	9.1	5.1	11.2	8.9	8.7	7.7	7.4	6.6	7.6	11.3
	DA	9.9	14.3	9.0	8.1	10.4	6.8	4.4	5.9	7.2	6.1	8.3	7.3	2.0	3.4	4.3	5.0	6.6	7.3
	DL	19.5	19.3	26.2	21.5	19.8	18.3	7.4	20.7	23.5	19.3	16.7	21.4	11.4	10.8	9.9	11.5	15.3	16.7
	TR	12.6	11.8	11.7	12.3	9.4	10.2	11.3	12.5	11.8	10.9	9.3	9.9	3.3	4.3	5.0	5.3	6.7	6.9
Push Up	BB	8.7	8.5	9.6	8.4	8.6	7.0	14.6	13.0	11.3	15.3	9.6	16.1	16.2	10.2	10.0	14.6	9.7	11.1
	TB	9.5	9.6	8.9	11.7	10.5	11.9	11.0	5.6	11.0	7.7	10.3	6.7	4.2	3.3	3.4	3.7	5.0	4.2
	DA	23.8	20.3	15.4	25.6	18.9	22.0	22.3	16.4	16.8	17.2	11.3	13.5	9.2	7.4	8.4	8.8	9.1	7.0
	DL	13.3	11.8	17.8	11.1	18.0	12.3	7.5	5.4	13.0	8.5	16.6	8.8	6.8	5.0	7.4	6.6	14.3	8.8
	TR	15.5	14.5	15.2	16.7	17.0	14.3	15.2	9.2	16.6	23.4	12.0	15.7	11.4	9.6	12.3	12.9	13.3	13.2
Push Down	BB	6.2	9.4	2.7	6.9	3.8	13.1	2.7	3.2	2.6	3.8	2.7	1.8	4.4	4.4	3.3	5.6	3.8	3.9
	TB	12.0	7.1	14.2	9.8	11.7	7.3	12.3	7.5	15.5	10.7	13.3	11.5	13.0	14.1	11.7	12.3	12.5	13.6
	DA	8.1	5.9	4.2	8.2	4.7	6.5	5.7	3.8	7.0	3.1	3.6	2.4	3.2	4.0	2.1	2.2	2.2	2.0
	DL	3.4	3.4	4.0	3.7	5.6	3.5	5.1	4.9	4.4	3.5	4.3	3.6	7.7	7.0	4.2	3.1	2.6	3.9
	TR	3.6	4.2	3.8	4.0	4.1	5.5	5.3	4.2	4.4	4.2	3.9	4.8	5.9	4.7	4.8	5.1	4.3	4.4
Medial	BB	21.0	12.5	22.7	16.4	17.6	18.9	18.4	18.8	16.0	28.4	13.8	30.6	6.3	9.1	8.3	5.4	6.1	5.0
	TB	8.2	8.5	6.7	8.9	7.1	10.2	10.2	5.7	5.3	6.7	4.9	7.4	4.9	5.5	3.8	7.4	6.0	6.7
	DA	15.3	12.7	12.1	17.5	14.3	16.6	17.0	13.7	9.9	9.9	7.4	6.5	9.1	5.4	7.9	3.3	3.9	2.8
	DL	10.7	15.2	8.8	9.6	15.1	11.0	5.6	5.7	6.9	6.5	7.8	7.3	2.0	1.4	2.2	2.5	2.0	2.2
	TR	12.1	14.9	11.6	14.1	16.3	15.2	8.8	11.0	8.5	10.4	7.5	11.7	3.5	2.5	3.0	1.8	1.6	4.1
Lateral	BB	7.9	8.1	6.0	6.6	8.1	4.8	8.0	9.0	9.2	8.5	4.9	7.6	12.5	7.3	7.5	9.4	9.0	10.9
	TB	17.3	13.7	22.5	21.3	26.1	21.8	19.1	12.8	22.1	15.3	15.4	14.8	11.0	13.5	8.8	11.0	9.4	11.0
	DA	4.1	3.2	6.9	5.4	6.0	5.3	7.5	8.6	7.8	7.2	5.8	6.8	8.2	9.4	8.0	8.2	8.9	9.1
	DL	17.1	14.0	14.2	17.8	15.3	9.8	17.7	16.6	18.1	14.2	12.6	6.2	17.6	13.5	13.5	12.8	13.3	17.7
	TR	6.5	8.4	5.9	5.4	5.3	6.4	9.5	10.2	7.8	7.6	7.1	5.2	7.4	9.8	9.5	7.0	9.0	9.2

APPENDIX D

Table 15: Conversion from study conditions to H, V, and L distances from the shoulder joint at (0,0,0). These data were used in the regression equation development.

Condition			Location in cm		
Height	**Angle (°)**	**Reach %**	**Vertical**	**Horizontal**	**Lateral**
High	0	80	100.0	43.6	0.0
High	0	40	100.0	22.2	0.0
High	45	80	100.0	30.8	30.8
High	45	40	100.0	18.0	18.0
High	90	80	100.0	0.0	43.6
High	90	40	100.0	0.0	22.9
Med	0	80	82.0	47.2	0.0
Med	0	40	82.0	23.7	0.0
Med	45	80	82.0	33.4	33.4
Med	45	40	82.0	17.2	17.2
Med	90	80	82.0	0.0	47.2
Med	90	40	82.0	0.0	23.6
Low	0	80	48.5	33.3	0.0
Low	0	40	48.5	2.1	0.0
Low	45	80	48.5	23.5	23.5
Low	45	40	48.5	6.1	6.1
Low	90	80	48.5	0.0	33.3
Low	90	40	48.5	0.0	6.2

VITA AUCTORIS

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