AN EVALUATION OF FEMALE ARM STRENGTH PREDICTIONS

AN EVALUATION OF FEMALE ARM STRENGTH PREDICTIONS

BASED ON HAND LOCATION, ARM POSTURE AND FORCE DIRECTION

By

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ABSTRACT

The primary purpose of this thesis was to measure arm strengths, in combinations of exertion directions, and to evaluate the importance of knowing the precise posture of the arm and specific joint locations in 3D space when predicting female arm strength. A stepwise multiple regression approach was utilized in the prediction of female arm strengths, using kinematic measures of hand location, arm posture and 26-force directions from 17 subjects and 8 hand locations as inputs. When including measures of arm posture, the regression model was indeed improved, explaining 75.4% of the variance, with an RMS error of 9.1 N, compared to an explained variance of 67.3% and an RMS error of 10.5 N without those postural variables. A comparison was also made between the empirical strength data from this thesis and the outputs from the University of Michigan's Center for Ergonomics 3-Dimensional Static Strength Prediction Program (3DSSPP) software. A poor correlation (R-square = 0.305) and high RMS error (39 N) was found, indicating a definite need for further evaluation of the 3DSSPP package, as it is one of the most commonly used ergonomic tools in industry.

DEDICATION

This thesis is dedicated to my late father, Dr. Paolo La Delfa.

You've definitely set one high bar I'll probably never reach,

but I certainly will try.

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First of all, I would like to thank my thesis advisor, Dr. Jim Potvin, for his continued support and unbelievable guidance over the years. His uncanny attention to detail and ability to separate work from personal life are valuable traits that I have certainly come to appreciate and hope to one day emulate. I truly am greatful for the trust he has shown in me from the beginning, and continues to show me on a daily basis. On that note, let us hope in my PhD I can "be less ______".

I would also like to thank all my labmates and friends at McMaster. I am so lucky to get to spend the majority of my time with such a good group of people, and really look forward to whatever boshly antics we get ourselves into in the coming years.

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Lastly, I would like to thank my fiancée and love of my life, Laura. Just like our high school days, she has always been my #1 fan and has inundated me with unwaivering support in every aspect of my life. I very much look forward to our life together!

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CHAPTER 1 - INTRODUCTION

There are a multitude of jobs in the industrial workplace that require employees to exert repetitive arm exertions while grasping an object in the hand. These repetitive hand forces, often performed with the arm in awkward postures and/or with overhead hand positions, place unique challenges on the shoulder complex, which can lead to repetitive strain injuries (Grieve & Dickerson, 2008). These injuries not only cause significant pain and suffering to the worker, but also a financial burden to employers in the form of increased compensatory costs and lost productivity. According to the Workplace Safety & Insurance Board's (WSIB) annual report (2008), there were 312,315 total claims registered in the province of Ontario resulting in 78,256 accepted lost time claims. Many of the common injuries that occur in the workplace have been related to various risk factors including posture, repetitive activities, excessive forces and poor task design (Anton et al., 2001; Das & Wang, 2004; Forde & Buchholz, 2004; Garg, Hegmann, & Kapellusch, 2005; Grieve & Dickerson, 2008).

There is a large body of research that has examined work related injuries and associated risk factors of the upper extremity and shoulder. Injuries such as tendonitis, tenosynovitis, thoracic outlet syndrome and bursitis have consistently been reported in the literature as common work-related shoulder ailments (Abe, Ichinohe, & Nishida, 1999; Das & Wang, 2004; Haslegrave, Tracy, & Corlett, 1997;

Putz-Anderson, 1992; Svendsen, Bonde, Mathiassen, Stengaard-Pedersen, & Frich, 2004). In an effort to reduce these workplace injuries, numerous studies have focused on reducing the above-mentioned risk factors associated with posture, repetition and force. This mirrors the effort contributed by employers who are currently trying to reduce work place injuries by developing jobs that place minimal stress on their employees.

Strength measurements are used in industry to plan safe manufacturing designs so that an organization can simultaneously optimize their production efficiency while lowering the amount of worker days lost to injury (Peebles & Norris, 2003). There have been large amounts of data collected in a joint effort to determine and set threshold limit values (TLVs) for work related tasks (e.g. Mital, Nicholson, & Ayoub, 1993; Potvin, Chiang, Mckean, & Stephens, 2000; Snook, 1978; Snook & Ciriello, 1991). For example, landmark studies have set threshold limits for tasks such as lifting, lowering, pushing and pulling (Mital et al., 1993; NIOSH, 1981; Snook, 1978; Snook & Ciriello, 1991). These TLVs are often used in ergonomic tools that have been developed in an effort to aid both employers and ergonomists. Tools such as the Strain Index (Moore & Garg, 1995) and the Rapid Upper Limb Assessment (RULA) (McAtamney & Cortlett, 1993) are used to evaluate upper limb postures and injury risks and the NIOSH Lifting Equation provide upper weight limits for manual materials handling (NIOSH, 1981).

The University of Michigan Center for Ergonomics has developed and commercialized the 3-Dimensional Static Strength Predicion Program (3DSSPP), and it is one of the most popular quantitative ergonomic tools used in industry. The main use of the software is to evaluate the acute demands of various industrial tasks using a biomechanical approach, in an attempt to limit and reduce overall risk for injury. The 3DSSPP software allows the analyst to input posture and external force values, which it uses to calculate numerous outputs, such as spinal compression forces and the percentage capable of the strength requirements, in order to evaluate risk to the worker. Though 3DSSPP has provided companies with intuitive software to evaluate workplace ergonomics, its overall reliability may be questioned because the upper extremity strength data on which it is based are not very extensive, and small manipulations in posture may result in large differences in moments calculated at joints, as well as subsequent percent capable outputs. Another limitation of this software is that it may not always predict the appropriate worker posture due to individual factors such as job training, body composition and worker set-up preference. Furthermore, 3DSSPP is restricted to low frequency tasks and is not directly applicable to repetitive exertions (Mital, Nicholson, & Ayoub, 1993). As the majority of strength data for the 3DSSPP software comes from the approximately 30-45 year old work of Clarke (1966), Schanne (1972) and Stobbe (1982), a true critical evaluation of the 3DSSPP strength outputs is needed considering many important ergonomic decisions are being made with this software.

In an attempt to improve the arm strength models, there have been several more recent studies that have begun to quantify shoulder strength from a variety of perspectives. It has been determined that factors such as gross body posture, arm posture, gender and age contribute to shoulder strength (Chow & Dickerson, 2009; Das & Wang, 2004; Haslegrave, Tracy, & Corlett, 1997; Lannersten, Harms-Ringdahl, Schuldt, Ekholm, & Group, 1993; Peebles & Norris, 2003; Potvin, Petruzzi, Avrahami, & Freeman, 2010; Stobbe, 1982). Potvin et al. (2010) integrated data from Freeman & Potvin (2008) with new data collected from studies measuring female arm strengths in a variety of exertion directions, hand locations, reach distances and hand postures. This collection of data resulted in very accurate predictive regression equations for maximal hand force capabilities. Within this research, predictions of force in the six primary directions (up, down, push, pull, medial and lateral) were possible based on only the location of the hand with respect to the shoulder.

In an applied sense, it is fairly uncommon to see arm exertions in purely one of the primary directions in the workplace. Therefore, being able to validly predict arm strength in any combination of these primary directions is of particular practical importance, and a logical extension from the fairly reliable prediction of one-dimensional arm strength (Roman-Liu & Tokarski, 2005; Freeman, 2006; Potvin et al., 2010). A 1-dimensional (1D) exertion is defined as the direction of force application being in one of the primary six directions (up, down, push, pull, medial or lateral). A two-dimensional (2D) exertion is any effort along a plane comprised of two of the 1D axes (e.g., up and medial); and a 3-dimensional (3D) exertion is any exertion with components along three orthogonal axes (e.g., push up, pull back and exert medial)(Figure 1.1). Potvin et al. (2010) summarized data from 1D, 2D and 3D force directions with respect to the shoulder. As mentioned above, the estimates of 1D force were very good (R-square of 92.5% and RMS error of only 6.4 N), however, the equations combining 1D, 2D and 3D data did not perform as well in predicting shoulder strength in those combinations of directions (R-square = 0.626, RMS Error = 17.1 N). Despite the predictive success using only the horizontal (H), vertical (V) and lateral (L) location of the hand as inputs into the 1D equations, these three variables do not explain enough variance and lacked the necessary information to predict more complex combinations of force directions. It is proposed that additional information about elbow location, shoulder location and arm posture may add to the explained variance for exertions for any combination of hand location and exertion direction.

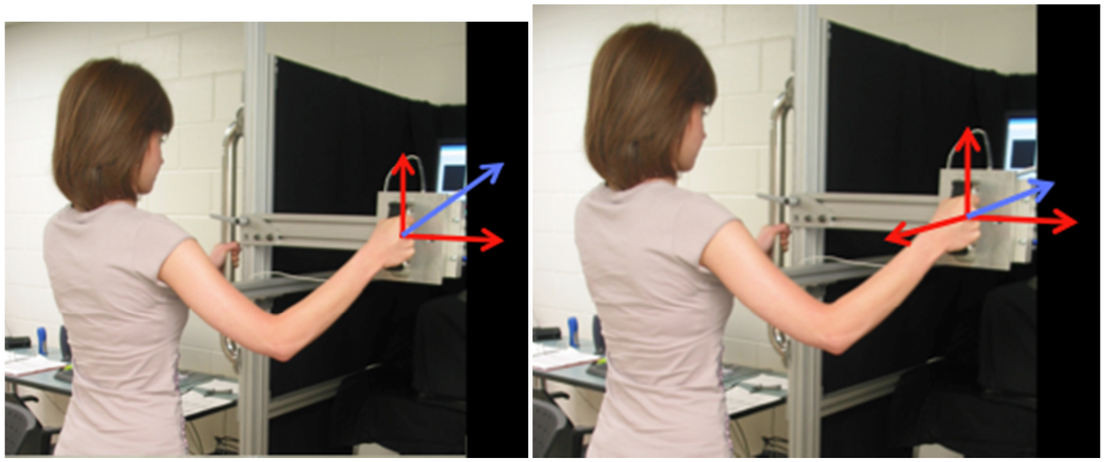


Figure 1.1: An example of a 2D exertion (left image) and a 3D exertion (right image). In the images, the red arrows represent the directions of force exertion and the blue arrows represent the resultant force, therefore the 2D exertion is composed of a push and right effort and the 3D exertion is composed of an up, right and pull effort.

1.1 Statement of Purpose

The primary purpose of this thesis was to measure arm strengths in 1D, 2D and 3D exertion directions and evaluate the importance of knowing the precise posture of the arm and specific joint locations in 3D space during maximal arm exertions. In particular, elbow location and upper limb angles may provide important information about how subjects optimize 3D moment arms and use their arm posture in an advantageous way to maximize strength, particularly in the 2D and 3D exertion directions where successful predictions have not yet been achieved, likely due to insufficient information within the inputs.

Another component to this thesis examined the relationship between 3DSSPP arm strength prediction software strength outputs and the empirical data measured in a lab. This will be done by comparing the 3DSSPP maximal acceptable force outputs for a 50th percentile female, which is generally considered to be the 50-pecent capable estimations, against the actual arm strength measurements for the given force directions and hand locations made during this thesis, in combination with the strength data compiled by Potvin et al (2010). Given that the 3DSSPP software is used widely in industry, it is important to validate it against an extensive set of empirical arm strength data so that improvements can be made, if necessary.

1.2 Hypotheses

1) It is hypothesized that by knowing the location of the elbow and the posture of the arm during the maximal exertions, one general multidimensional regression equation will be able to be developed with good predictive accuracy (R-square of over 81%) of average arm strength at any hand location in the reach envelope tested. It is expected that this equation will explain more variance and have a reduced RMS error when compared to a similar equation developed excluding the elbow location terms and postural information, such as the shoulder and elbow angles.
2) It is hypothesized that a continuous trend in strength will be observed at interpolated hand locations within the hand locations tested in this thesis.
3) As is claimed by the University of Michigan Centre for Ergonomics (2006), it is hypothesized that the 50-percent capable estimations for each hand

location and 1D exertion direction will correlate strongly (r = 0.8) with those collected in this thesis and in Potvin et al. (2010). It is expected that the average errors will be evenly distributed between being over and under-predictions of strength.

CHAPTER 2 – REVIEW OF LITERATURE

2.1 Workplace Injuries and Risk Factors

2.1.1 – Workplace Injuries

There is a large body of research that has examined work related injuries and associated risk factors that occur in the upper extremities and shoulder. In an effort to reduce serious workplace injuries such as tendonitis, tenosynovitis, thoracic outlet syndrome and bursitis, researchers have focused numerous studies on correcting well-known risk factors such as posture, repetition and force. The reduction of workplace injuries and ergonomics in general has also become a more common goal amongst employers. According to Snook (1978), if jobs are not designed to be acceptable to at least 75% of the population, a worker is three times more likely to suffer a lower back injury. Therefore, strength measurements and tools to assess ergonomic risk are used in industry to plan safe manufacturing designs so that an organization can optimize their production efficiency while lowering the amount of worker days lost to injury (Peebles & Norris, 2003).

2.1.1.1 – Shoulder Injuries and risk factors

The cost of upper extremity and shoulder injuries to industry has been extensive. In 2001 alone, more than 90,000 shoulder or upper arm injury and illness cases were reported across all private industry, resulting in a rate of 9.7 shoulder injuries and illnesses per 10,000 full-time workers in the United States. These occupational shoulder injuries caused a median of twelve lost working days (Bureau of Labor

Statistics, 2004). Out of a total of 78,256 injuries reported to the WSIB in Ontario in 2008, 3,411 (4.4%) were attributed to the 'arm' and 5,376 (6.9%) were attributed to the 'shoulder' for a total of 8,787 injuries (11.2%) attributed to the two (WSIB, 2008). It is quite apparent from the above statistical data that, despite the relative increase in ergonomic awareness and research that has focused on determining ways to alleviate or limit risk factors, upper extremity injuries still occur.

According to Putz-Anderson (1992), there are three general types of injuries that can occur in the shoulder: tendon disorders, nerve disorders and neurovascular disorders. Inflammation of the tendon, or peri-tendonitis, is one of the more common forms of workplace injury and usually occurs when the smooth gliding motion of the tendon is impaired, or when repeated tensioning aggravates the tendon. This hindered motion of the tendon causes irritation and is often associated with pain during contractions of the acting muscle.

Tendonitis of the rotator cuff tendons is one of the more common types of tendonitis in the workplace, especially during overhead work (Hagberg & Wegman, 1987; Svendsen et al., 2004). This is partially due to the small bony passage bordered by the humerus and the acromion, through which some of shoulder tendons pass. Studies have shown that the common causes of rotator cuff tendonitis include working with the arm(s) elevated, maintaining static contractions and not having adequate rest between repetitive motions (Grieve & Dickerson, 2008; Svendsen et al., 2004).

Another overexertion injury that can occur at the shoulder joint is bursitis. A bursa is a fluid filled sac 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. Repeated exertions of the shoulder muscles can cause inflammation at the subacromial-subdeltoid bursa leading to pain, especially during work with the arms abducted or flexed overhead for extended periods of time (Grieve & Dickerson, 2008). Another common overuse disorder at the shoulder, with a more neurological basis for pain, is thoracic outlet syndrome. This condition is generally caused by entrapment of the brachial plexus, which is compressed, stretched and twisted in the thoracic outlet (Abe, Ichinohe, & Nishida, 1999). Painful symptoms of thoracic outlet syndrome are mainly neurological in nature, however vascular compression can often occur in some cases, increasing the immediate severity of the disorder. In many cases, the combination of symptoms would lead to a decreased ability to exert forces due to pain and the possible motor disturbances (Abe, Ichinohe, & Nishida, 1999).

It is well noted that the risk for shoulder injury is likely increased by performing tasks with the hands above the height of the shoulders (Anton et al., 2001; Grieve & Dickerson, 2008; Roman-Liu & Tokarski, 2005). By examining epidemiological, biomechanical and physiological research, it is becoming evident that overhead work: increases muscle activation leading to greater muscular fatigue, produces tendon and nerve impingements, and changes the skeletal and muscular dynamics of the shoulder complex. These risk factors are further supported by epidemiological evidence showing a marked increase in musculoskeletal disease amongst workers who frequently engage in overhead work (Grieve & Dickerson, 2008).

The other common risk factors when dealing with workplace shoulder injuries is the combination of repetitive static contractions with a lack of sufficient rest time. An increased rate of musculoskeletal complaints in the neck and shoulder, correlated to an increasing level of static muscle activity of the upper trapezius muscle, has been reported for groups of workers (Westgaard, Waersted, Jansen, & Aaras, 1986). Veiersted, Westgaard, & Andersen (1990) have noted that prolonged loading and elevated activation levels with fewer rest periods, conditions common in several occupational tasks, have also led to an increased pain reporting.

2.1.1.2 – Neck Injuries and risk factors

Occupational neck pain is a form of injury that is not limited to any particular work setting. According to a review by the Bone and Joint Decade 2000–2010 Task Force on Neck Pain and its Associated Disorders, the reported annual prevalence of neck pain ranged between 27.1% and 47.8% in general population surveys of workers, and that neck pain interfered with the daily activities of between 11% and 14.1% of workers annually (Cote et al., 2008). Individuals who suffer from chronic neck pain also often exhibit other symptoms such as headaches with pain in the jaw and thoracic region. 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; Cote et al., 2008). There has been much research to suggest that working with the head deviated from a neutral posture can lead to both shoulder and neck pain (Cote et al., 2008; Fordyce, Morimoto, Coalson, Kelsh, & Mezei, 2010; 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, Ragland, Greiner, Syme, & Fisher, 1997).

2.2.1.3 – Elbow Injuries and risk factors

Elbow epicondylitis is one of the most prevalent disorders of the arm causing a functional loss of muscle strength and pain. Lateral epicondylitis is commonly called "tennis elbow" and medial epicondylitis is called "golfer's elbow". Elbow epicondylitis is clinically defined by pain in the region of the lateral and medial epicondyle (Figure 2 in 2.1.1), which is provoked by resisted use of either the extensor or flexor muscles of the wrist, respectively (Shiri, Viikari-Juntura, Varonen, & Heliovaara, 2006). It produces a significant economic burden through lost workdays and, in some patients, inability to work may last for several weeks (Armstrong, 1996; Shiri et al., 2006). According to Shiri et al. (2006), there is still insufficient evidence to support a relationship between epicondylitis and exposure to repetitive work alone, however, there is evidence of an association of epicondylitis with forceful work tasks, repetitive activities in the upper extremity and extreme postures of the hands and arms.

2.1.3 – Ergonomic tools to address workplace upper extremity injuries

There have been a number of tools developed based on TLV research when taking into account risk factors such as posture, force and repetition (McAtamney & Cortlett, 1993; Mital et al., 1993; Moore & Garg, 1995). In general, the functionality of these tools is enhanced by being easy to use, ergonomically valid and adaptable to a variety of tasks.

With the increasing prevalence of office work and the everyday occupational use of computers, there is a noticeably increasing trend towards upper limb musculoskeletal disorders (Gerr, et al., 2002; Village, Rempel, & Teschke, 2005; Wahlstrom, 2005). Repetitive motion of the fingers, hands and wrists, sustained awkward postures of the wrist and forearm, and contact pressures in the wrist have been proposed as possible mechanisms of injury related to the use of the keyboard and mouse (Village et al., 2005).

According to Moore & Garg (1995), there is a lack of practical physiological, biomechanical or psychophysical models that relate job risk factors to increased risk of developing distal upper extremity disorders. In an attempt to identify jobs associated with distal upper extremity disorders, Moore & Garg (1995) developed the Strain Index. The Strain Index tool is rather simple to use and is based on principles of physiology and biomechanics, as well as taking into account epidemiological information realting to distal upper extremity disorders. The Strain Index involves the measurement or estimation of six task variables, including:

intensity of exertion, duration of exertion per cycle, efforts per minute, wrist posture, speed of exertion and duration of the task per day. Each of these task variables are assigned an ordinal rating and according to the exposure data, a multiplier value is assigned to each task variable. Of these task variables, the intensity of exertion task variable has the largest influence on the overall strain index score, with duration per day and speed of work having the lowest multiplier scores, and therefore the least influence on the overall score (Figure 2). The relatively high weighting of intensity of exertion was based on previous research indicating that high forcefulness and repetitiveness were the best predictors for the prevalence of carpal tunnel syndrome and other tendon-related disorders (Moore & Garg, 1995). A limitation of the Strain Index is the general assumption that the relationship between risk of upper extremity disorders and the task variables is multiplicative. It is fully disclosed by the authors that the relationship between the incorporated task variables and the multipliers were based on their best judgment and not supported experimentally. Also, much like many of the other assessment tools, the Strain Index is suscpetible to subjective qualitative ratings, including the highly weighted intensity of exertion task variable.

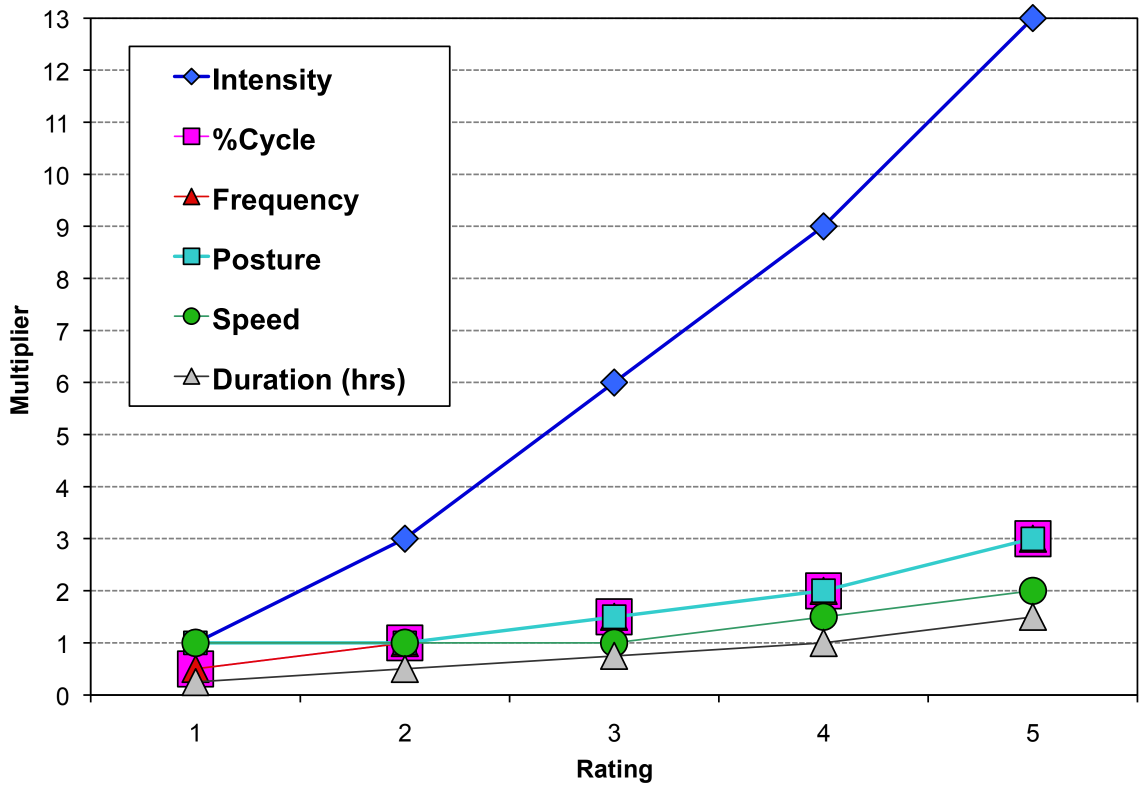


Figure 2.1: Task variable multipliers within the Strain Index (Moore and Garg, 1995). Each task variable's multiplier score is plotted against the measured or subjective rating given for the score. Note that the intensity variable has the highest overall impact on the Strain Index final score and duration has the lowest.

With the goal of providing a rapid assessment tool for the upper extremity, McAtamney & Cortlett (1993) designed the Rapid Upper Limb Assessment (RULA) tool. RULA was designed to investigate the exposure of individual workers to risk factors associated with work-related upper limb disorders. The key factor to RULA's subsequent success as an ergonomic tool is its relative ease of use and the fact that it is an observational screening tool that does not require the use of any external tools or any significant specialized training. RULA is not meant to be a final decision maker, but rather an assessment tool that can prioritize certain jobs and tasks based on standard known risk factors and providing the assessor with a grand risk score from 1 to 7, with the score increasing as the risk does (McAtamney & Cortlett, 1993).

2.2 – Assessment of Strength

According to Snook (1978), if jobs are not designed to be acceptable to at least 75% of the population, a worker is three times more likely to suffer a low back injury. For this, and many other reasons, manufacturers must take into account the acceptable levels of force production for each of their workers. By having a comprehensive understanding of the joint strengths of individuals and groups of people, we can begin the make more valid decisions about safe designs and tasks for the working population.

There are a number of different ways to represent human joint strength. The primary modalities discussed in the literature include isometric, isotonic and isokinetic strength tests. It is, therefore, of the utmost importance for ergonomic research to collect data looking at force production for a large variety of tasks to: 1) determine the actual strength of humans and 2) determine what factors have a significant effect on strength and must be accounted for in the design of jobs. With accurate strength data, engineers, ergonomists and designers can attempt to accommodate as many people as possible in their designs. Furthermore, once confident with the fidelity and breadth of the available strength data, methods to accurately predict human strength can be developed and incorporated into human digital models, thereby enhancing their functionality as a valuable ergonomic aid.

The two most common types of strength testing are dynamic and static tests. Dynamic strength tests have been available for many years, however isometric or static testing has remained the preferred method in many workplace studies due to its relative simplicity in occupational settings (Essendrop, Schibye, & Hansen, 2001). The general consensus remains that, for dynamic tasks, dynamic strength tests should be used and conversely, static strength tests should be used for static muscle tasks (Mital & Kumar, 1998).

2.2.1 – Dynamic Strength Testing

Dynamic strength tests involve the measurement of strength while the effector is being moved by an eccentric or concentric contraction. Mital and Kumar (1998) define dynamic strength testing as the form of strength testing in which the joint angles and body segment positions change during the exertion. Isokinetic strength testing is defined as having a rate of shortening or lengthening that is kept constant during muscular exertions. Functionally, isokinetic strength testing would be used to measure a person's maximal voluntary contraction when the joint angle is changing at some constant speed (Chandler, Kibler, Stracener, Ziegler, & Pace, 1992; Mital & Kumar, 1998). On the other hand, isotonic force testing is characterized by maintaining a constant force during the contraction. The inherent difficulty in interpreting and using dynamic strength test data is that, during the movement, there is a constantly changing moment arm as well as a change in the length of the muscle fibres, which will both contribute to a change in the muscle moment that is produced (Mital & Kumar, 1998).

2.2.2 – Static Strength Testing

Static strength testing is the more common method for measuring human strength (Essendrop et al., 2001). It measures the capacity for a person to exert a maximal force in a single isometric contraction, meaning that, in most cases, the strength is evaluated at some predetermined location or joint angle. Though static tests may not be the most accurate representation of some dynamic tasks, they are still useful in providing an elementary understanding of human strength because of their ability to control for variables such as changing posture and the type of contraction.

Continuous static strength testing is a type of static strength test employed with the goal of recording how the strength declines during a sustained contraction, therefore giving a representation of endurance time (Mital & Channaveeraiah, 1988). Repetitive, static strength testing is another modality of measuring static strength that looks at the maximal exertions applied at given frequencies and includes allotted rest periods in which the muscle can recover between exertions, therefore including a psychophysical component.

2.2.3 – Shoulder Strength Data

There have been numerous studies that have collected shoulder strength data in the in a number of manners (Das & Wang, 2004; Freeman, 2006; Garg, Hegmann, &

Kapellusch, 2005; Haslegrave, Tracy, & Corlett, 1997; Rohmert, 1966; Rohmert & Jenik, 1971; Lannersten, Harms-Ringdahl, Schuldt, Ekholm, & Group, 1993; Peebles & Norris, 2003; Roman-Liu & Tokarski, 2005; Stobbe, 1982). Many of these studies have taken different approaches to evaluating shoulder strength and examined many different factors that have an effect on shoulder strength measurements, especially posture. This review will focus on some of the significant landmark shoulder strength studies that have had a large impact on both the pursuit of valid shoulder strength measurement and industrial ergonomic practice.

A large proportion of the strength data used in the University of Michigan's 3DSSPP software come from Stobbe (1982). The purpose of Stobbe's work was to determine whether functional muscle group strengths, required in typical industrial work, could be accurately predicted from the results of a set of standardized, multiple muscle, strength tests. The study consisted of 67 subjects (35 males and 32 females) who were divided into two groups based on age. Both university students and non-university students who were volunteers from three industrial plants. Stobbe conducted general isometric testing of the arm, shoulder, lower back, abdomen, thigh and leg. In order to calculate maximum forces that can be exerted at the hand with the shoulder muscles, Stobbe had seated and constrained subjects exert forces against a resistance to the distal end of the humerus or the proximal end of the forearm. The shoulder axes Stobbe tested were medial and lateral humeral rotation, horizontal shoulder strength in the forward and backwards direction, shoulder adduction and shoulder abduction (Figure 2.2). During these shoulder tests, the subject's movement was limited by straps that kept the torso relatively immobile. As well, the subjects' feet hung freely from the chair and not allowed to make contact with the floor during the exertions. All six test positions were selected based on previous maximal strength findings from primarily Schanne (1972) and Clark (1966). Stobbe's research resulted in a fairly comprehensive strength database for both males and females in the six specific directions that were tested, as well as several other body segments that were also tested in the thesis.

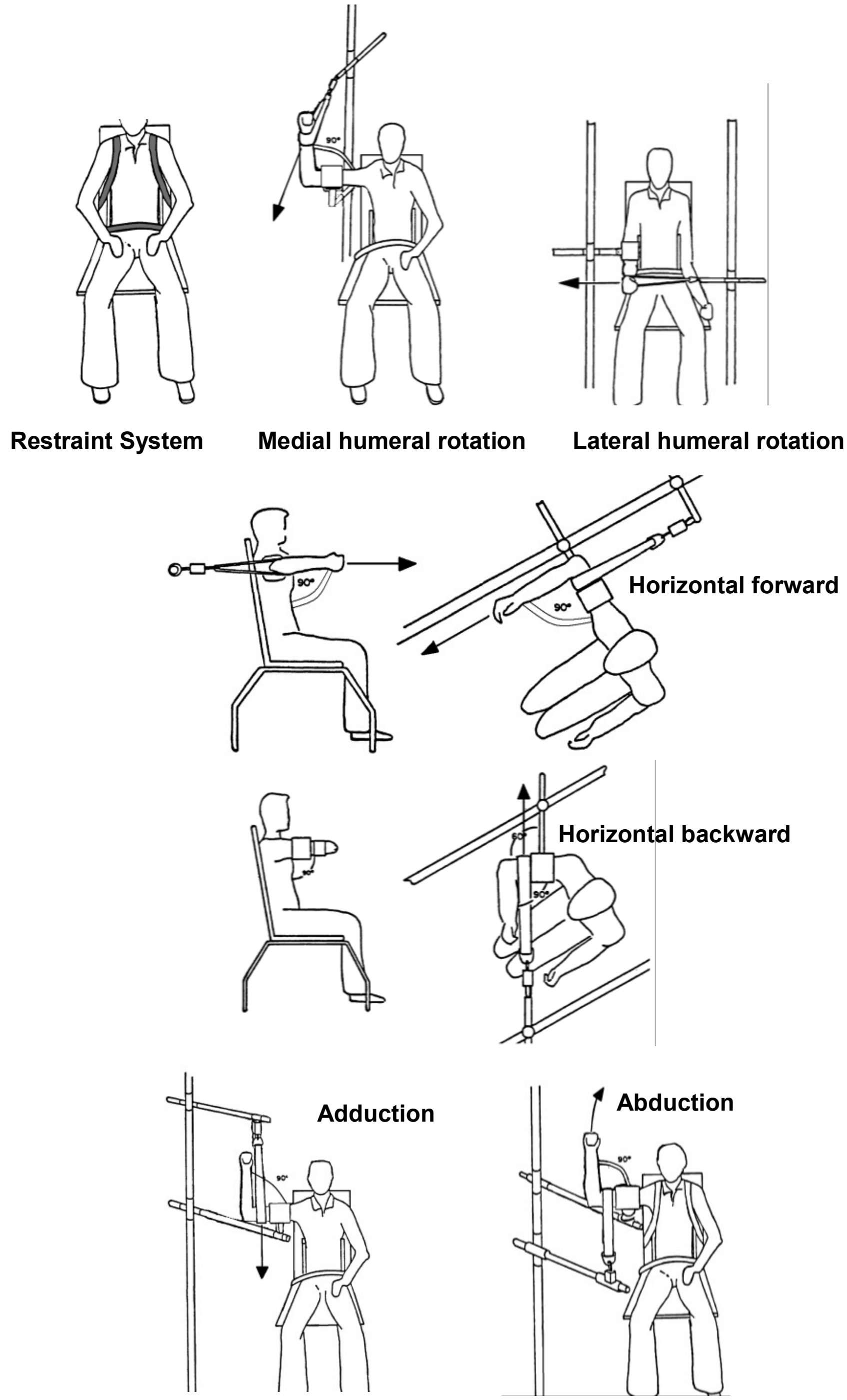


Figure 2.2: Testing apparatus and testing positions for the six different functional shoulder strength tests in Stobbe (1982). Subjects were required to exert forces against a resistance to the distal end of the humerus, or proximal end of the forearm. *Freeman (2006), originally adapted from Stobbe (1982)*

Aside from developing a comprehensive functional strength database, another component to Stobbe's (1982) dissertation was the development of predictive regression equations for functional strength developed from the standard strength measurements. In order to reduce the methodologically induced variance, Stobbe used a rigorous subject restraint and measurement system in an attempt to achieve an accurate prediction model. Stobbe came to the conclusion that functional strength regression models based upon selected standard strength data seemed to be the best way of producing predictive equations (R-square = 63% to 89%, with a mean of 79%). Functional strength models based on only anthropometric data were found to be less accurate (R-square = 43% to 73%, with a mean of 60%), while the more complicated models that included standard strength as well as all the complex anthropometric measurements yielded a slight improvement in model accuracy (R-square = 67% to 93%, with a mean of 84%). Despite there being more explained variance in the more complicated model, Stobbe (1982) came to the conclusion that the difficulty of including the anthropometric measurements was not worth the added explained variance in a practical setting. In other words, the 5% gain in expalined variance was not worth the effort or expertise that would be needed to collect the anthrometric body measurements required. In general, the equations tended to over-predict subject strength, which in the workplace is an undesirable error since the model is predicting that workers are stronger than they are, thus leaving them susceptible to injury. Stobbe attributed much of the overprediction to subjects producing sub-maximal efforts on the collection of the MVC data. It should also be noted that these predictive equations include strength data from both genders. Upon analysis of gender specific models (ie, female or male only), the prediction accuracy was much lower than with the gender-combined model for no strong reason other than there being a smaller sample size.

Though Stobbe's (1982) thesis represents an important step in strength research, and some of the most complete data compiled to date, it lacks the necessary detail to provide accurate and confident predictions of shoulder strength in numerous complex working positions. As previously stated, in Stobbe's isometric 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, therefore raising questions as to its applicability in a workplace setting. Another potential concern with the methodology is that between the shoulder and the hand, there are four degrees of freedom in the model; 3 at shoulder and 1 at elbow. This creates a situation in which there is susceptibility to error in four regression equations, with each additional error potentially compounded by the previous one (Freeman, 2006). Another main limitation of Stobbe's work was the relatively few postures tested for each functional strength test. Each functional strength test was only completed in one posture, those that were predicted to be the ideal posture for maximal moment production based primarily on Clark (1966) and Schanne (1972).

2.2.5 – Factors effecting shoulder strength

2.2.5.1 – Posture

There have been numerous studies that have examined the effect of postures on shoulder and arm strength (i.e. Chow & Dickerson, 2009; Das & Wang, 2004; Freeman, 2006; Haslegrave et al., 1997; Lannersten et al., 1993; Potvin et al., 2010; Roman-Liu & Tokarski, 2005; Stobbe, 1982; Svendsen et al., 2004). In order for valid predictions of strength to be made, it is paramount to understand how posture can affect different types of shoulder exertions. Knowing this information will enhance the predictive power of future shoulder strength models.

Realizing that there was a gap of strength data with subjects in "awkward" postures, something that is very prevalent in the workplace, Haslegrave et al. (1997) collected static strength data for three awkward postures: standing twisted sideways, standing working overhead, lying supine and working overhead, and standing facing forward as a control. Subjects were required to exert maximal push forces in a variety of directions at hand locations that were standardized and determined based on the individual's anthropometry. By focusing on awkward postures that would likely be seen in the workplace, Haslegrave et al. (1997) showed that even small constraints on posture within the workplace may have a large effect on the ability to exert force. The mean forces exerted for the different directions of force application had a very large range depending on what posture the participants were in. For example, while standing, a horizontal push forward at shoulder height resulted in a mean force of 277±106 N, while a similar push while lying supine and working overhead resulted in a mean force of 96±34 N (35%).

There has also been several studies looking specifically at strength in overhead positions. Garg, Hegmann, & Kapellusch (2005) determined maximum voluntary force as a function of shoulder angle for one-handed lifts. The study measured six different postures that were commonly used in automobile assembly tasks contained within the sagittal plane of the right arm. Some of the exertions occurred well below shoulder height and some were nearly directly overhead (150° of shoulder flexion and 180° of elbow extension). This study revealed that, for a lift and hold exertion in which subjects were required to lift the weight and hold it at the desired location, the strongest posture occurred below shoulder level at 0° of shoulder flexion with a 90° elbow angle (mean MVC = 88.3 ± 16.5 N). The weakest posture was at 90° of shoulder flexion with the elbow angle at 120° putting the hand overhead and in front of the head (MVC = 64.8 ± 13.3 N). Interestingly, as the shoulder flexion angle increased to 150° with a fully straight arm (180° elbow extension), the shoulder strength increased to 79.5 ± 19.1 N. This is most likely due to the decreasing moment arm from the shoulder to the hand as the shoulder angle increases.

Chow & Dickerson (2009) performed a study in which the overhead shoulder strength was evaluated, while sitting and standing, as a function of hand location and force direction. The study only included ten, right-handed female University students and three independent variables were manipulated: the direction of force exertion (vertical, horizontal and lateral – based on the industrial use of hand torque wrenches), angle of shoulder flexion from horizontal plane (0°, 30°, 60° and 90°), as well as gross body posture (sitting or standing), for a total of 24 test conditions. Much like Freeman (2006), arm posture was self-selected and only constrained by the point of force application on a handle. Position data were collected, however not presented. Chow & Dickerson examined if there were any effects or interactions between the conditions and used t-tests in order to determine that fatigue did not occur, as measured by no significant reductions in force. Their main conclusions were that direction of exertion had the greatest effect on shoulder strength when working at or above shoulder level, and the exertion with the greatest shoulder strength was vertically downwards. Also, they revealed that arm angle (to the horizontal plane) alone did not affect shoulder strength, however, when considered with exertion direction, shoulder strength increased as the relative shoulder flexion angle increased up to a maximum of 60°. This finding conflicts with Garg et al. (2005), who found that female strength increased as the shoulder flexion angle increased from the horizontal without any interaction effect with exertion direction. As these shoulder strength measurements were made on a small sample of university-aged females, the strength values may not be generalizable to a typical working population, however this testing methodology is consistent with similar studies conducted by Freeman (2006) and Potvin et al. (2010), which included substantially larger sample sizes and developed predective regression equations with the strength data that were measured.

2.2.5.2 – Gender

It has generally been observed that, on average, males tend to have greater strength than females (Lannersten et al., 1993; Peebles & Norris, 2003; Stobbe, 1982). In the study by Lannersten et al., (1993), women had 43%, 55%, and 56% of the men's strength in shoulder abduction, flexion, and external rotation, respectively. Peebles and Norris (2003) also found that, for all their collected grip strength measurements, males were significantly stronger than females, with female/male strength ratios ranging from 55% to 75% within their tested conditions. In Stobbe's evaluation of functional strength, he found relative strength differences between males and females to be in the 50% to 61% range rather than previously higher estimates. In general, the data obtained by Stobbe (1982) also showed that the relative difference of female strength compared to male strength tended to be smaller in the lower body compared to the upper body, so it is therefore important to make this distinction when designing manual tasks in the workplace.

2.2.5.3 – Age

There is also a large amount of research regarding strength changes related to age (Chaffin, Anderson, & Martin, 1999; Hughes, Johnson, O'Driscoll, & An, 1999; Peebles and Norris, 2003; Runge, Russo, Schiessl, & Felsenberg, 2004). According to Chaffin et al. (1999), the strength of the average person is greatest in the late twenties and early thirties. This strength, on average, is 5% less by age 40 and 20% less by age 60. Most research demonstrates a decrease in average strength as age increases. In a comprehensive examination of age-related changes in isometric shoulder strength, Hughes et al. (1999) compiled a normative database of twenty combinations of exertions and postures measuring shoulder strength, including: flexion, extension, abduction, adduction, internal rotation and external rotation. The cross-sectional study design included a large sample size of 120 subjects (60 men and 60 women) and ranged in age from 20 to 78 years of age. It was found that, in both males and females, age was negatively associated with all strength measures, again confirming the trend of a general decline in strength starting from the early twenties of age (Figure 2.3).

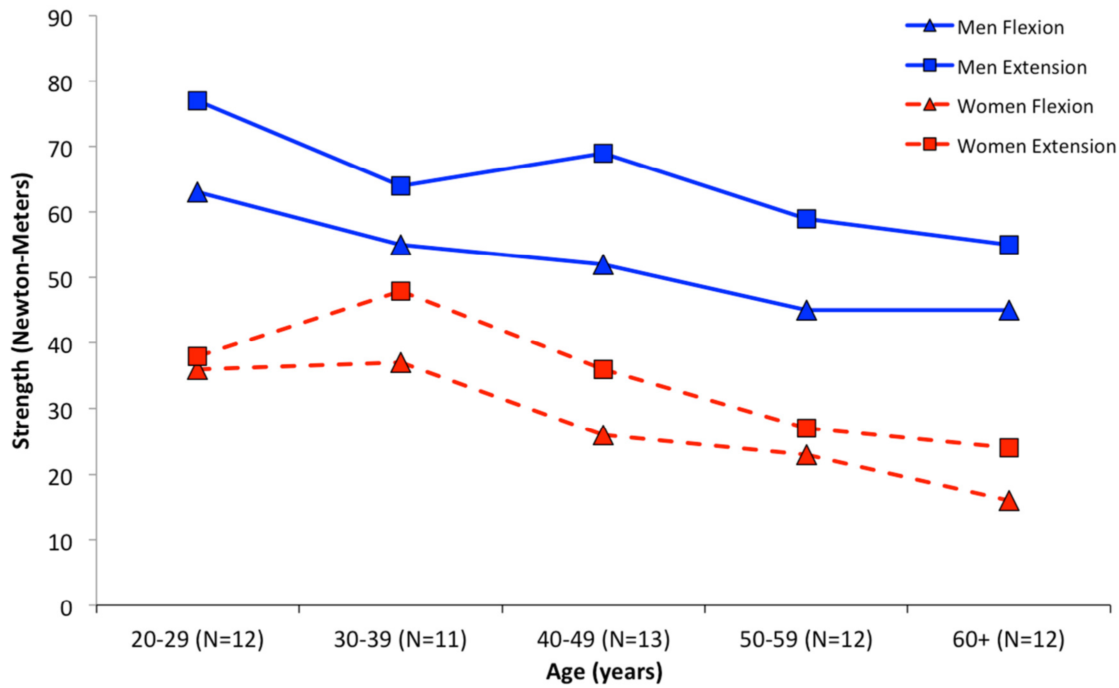


Figure 2.3: Sample of data from Hughes et al. (1999) showing both the age-related decline in strength as well as the difference in strength across genders. This figure shows dominant-arm strength measurements in Newton-Meters at a posture of 30° of arm flexion.

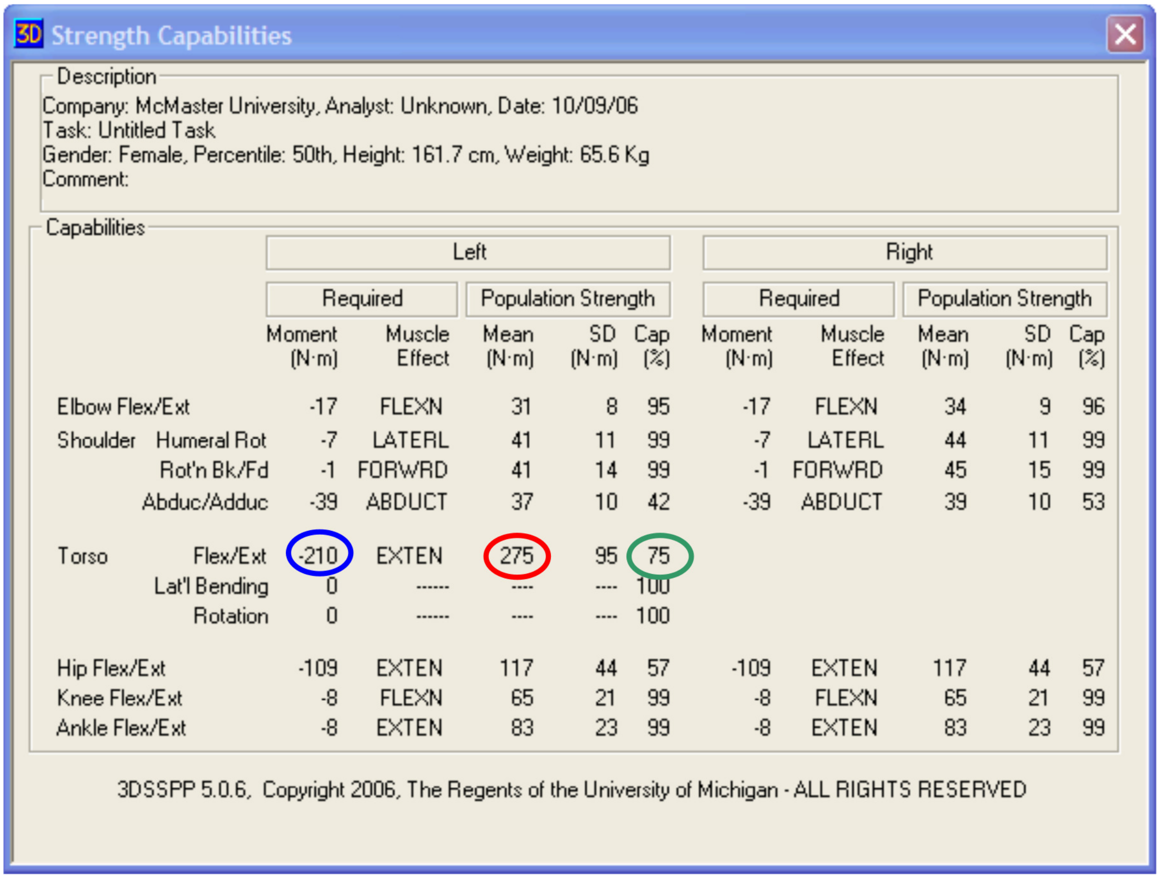
2.2.6 – Biomechanical prediction of strength

The use of biomechanical models in the prediction of strength can have large implications in the improvement of proactive ergonomics. If a methodology can be developed that would allow for accurate predictions of strength in any type of posture or task, the evaluation of workplace safety would have the potential to become much more efficient and effective. In order to produce a model with predictive capabilities, a detailed knowledge of the population's strength must be available beforehand. According to Stobbe (1982), there are two ways of collecting these data. The first would be to collect every strength characteristic by direct measurement. As previously discussed in this review, an approach of this nature would be daunting due to the vast amount of factors affecting strength. The next best, but more realistic, method is to estimate strength data based on predictive statistical estimation or regression equations. The major limitation to this method is that many of the strengths would be predictions that have not been empirically validated. However, this limitation can be substantially mitigated by collecting an expansive database of strength data at numerous locations within the reach envelope.

2.2.6.1 – 3-Dimensional Static Strength Prediction Program (3DSSPP)

The University of Michigan Center for Ergonomics has developed one of the most popular and commercially available ergonomic tools used in the automotive industry called 3-Dimensional Static Strength Predicion Program (3DSSPP) software. This tool can be used to analyze tasks and/or proposed workplace designs prior to the actual construction or reconstruction of the workplace or task. A particular usage of 3DSSPP is to evaluate low back compression, shear and other joint strength demands for a particular lifting condition, and then to compare these predictions to a standard in order to infer injury risk based on whether the task is acceptable to any percent of males or females. It should be mentioned that 3DSSPP is only useful in the analysis of static, or slow moving, manual handling tasks since the biomechanical computations assume that the effects of acceleration and momentum are negligable (The University of Michigan Center for Ergonomics, 2006). If one were to analyze a low-frequency dynamic task, the activity would have to be divided into a sequence of static postures that would be analyzed seperately.

Of particular interest to the current thesis is the static strength model that is utilized in 3DSSPP to evaluate joint strength demands. 3DSSPP utilizes a top-down link-segment model starting with the forces and moments applied to the hands and resolving with the forces and moments applied to the ground. In an optimization approach, the reactive moments at each joint that are required to maintain the inputted posture are compared to worker population strengths in the literature (The University of Michigan Center for Ergonomics, 2006). The software bases its predictive model of worker strengths on a compilation of empirical strength data from several studies, including Stobbe (1982), Schanne (1972), and Clark (1966). The individual joint moment outputs that were calculated from the optimization model, based on any combination of anthropometry, posture and hand load, are evaluated against the 3DSSPP population strength means (Figure 2.4). 3DSSPP produces a percent capable variable, which is the percentage of the population with the strength capability to generate a moment larger than the resultant moment at the joint. It is calculated as a function of the resultant moment, mean strength, and standard deviation of the mean strenth using a normal distibution. The University of Michigan Center for Ergonomics (2006) claims that the results from its strength model demonstrates a strong correlation of r = 0.8 with average population static strengths.


Strength Capabilities

Description

Company: McMaster University, Analyst: Unknown, Date: 10/09/06
Task: Untitled Task
Gender: Female, Percentile: 50th, Height: 161.7 cm, Weight: 65.6 Kg
Comment:

Capabilities

	Left					Right				
	Required		Population Strength			Required		Population Strength		
	Moment (N·m)	Muscle Effect	Mean (N·m)	SD (N·m)	Cap (%)	Moment (N·m)	Muscle Effect	Mean (N·m)	SD (N·m)	Cap (%)
Elbow Flex/Ext	-17	FLEXN	31	8	95	-17	FLEXN	34	9	96
Shoulder Humeral Rot	-7	LATERL	41	11	99	-7	LATERL	44	11	99
Rot'n Bk/Fd	-1	FORWRD	41	14	99	-1	FORWRD	45	15	99
Abduc/Adduc	-39	ABDUCT	37	10	42	-39	ABDUCT	39	10	53
Torso Flex/Ext	-210	EXTEN	275	95	75					
Lat'l Bending	0	------	----	----	100					
Rotation	0	------	----	----	100					
Hip Flex/Ext	-109	EXTEN	117	44	57	-109	EXTEN	117	44	57
Knee Flex/Ext	-8	FLEXN	65	21	99	-8	FLEXN	65	21	99
Ankle Flex/Ext	-8	EXTEN	83	23	99	-8	EXTEN	83	23	99

3DSSPP 5.0.6, Copyright 2006, The Regents of the University of Michigan - ALL RIGHTS RESERVED

Figure 2.4: An example of a Strength Capabilities report in 3DSSPP 5.0.6. Based on the result of the biomechanical analysis of a certain posture, hand load and anthropometry, a required moment is evaluated against predicted mean population strength and a percent capable (Cap %) is displayed. For example, the torso extensor strength is 275±95 Nm, such that the demand of 210 Nm is 65 Nm below the mean and the z-score is -0.68 which corresponds to a 25th percentile (75% capable) (The University of Michigan Center for Ergonomics, 2006).

Though 3DSSPP has provided an intuitive and efficient way to evaluate workplace ergonomics, the software suffers from some limitations. As can be seen with the referenced studies comprising the majority of the strength database (Stobbe, 1982; Schanne, 1972; Clark 1966), the data used in the percent capable analysis is quite old. A potential concern with the Stobbe (1982) strength data that was included in 3DSSPP is that the moment measurements were not taken at the hand, but rather closer to the elbow (discussed in section 2.2.4). Also, subjects in Stobbe's study were seated and fairly restricted with their torso during the measurements. As was discussed earlier, posture can have a significant effect on the strength of the upper limbs, especially in awkward (Haslegrave et al., 1997) or overhead postures (Chow & Dickerson, 2009), conditions for which 3DSSPP is used fairly often in industrual ergonomic analyses. Another limitation of this software is that it may not always represent the appropriate worker posture due to individual factors such as job training, body composition, worker set-up and user preference. As such, a critical analysis is needed of the 3DSSPP software's percent capable predictions since it is used so frequently in industry and important ergonomic decisions are being made with the assumption that the percent capable values are accurate despite not having a true validation.

2.2.6.2 – Other strength prediction studies

Building upon the main limitations of Stobbe (1982), Freeman (2006) conducted a comprehensive investigation of female arm strength in which he examined 29 non-skilled female subjects, of three separate age ranges representative of the work force, exerting maximal forces against a simulation device. Combinations of three heights (head, shoulder, and waist), 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). Freeman (2006) also collected electromyographic (EMG) data from 18 of the subjects to further analyze what was happening with the musculature of the arm and shoulder during the maximal contractions. Subjects were positioned as shown in Figure 1.1 and were required to exert a maximal voluntary force with their dominant hand in 20 hand positions (10 per testing session), comprised of the combinations of heights, angles and reaches listed above in each of the six exertion directions. For a trial to be considered valid, at least 90% of the resultant force had to be in the measured direction of exertion. The main purpose of the study was to measure the arm strength and develop regression equations that predict the maximal capabilities for hand forces exerted in the large assortment of hand positions and exertion directions. Two regression equations were developed for each of the six directions using a stepwise regression model. The first equation was developed for all exertions at or above shoulder height and the second was developed for all exertions at or below shoulder height. Variables used in the equations included horizontal distance (H), vertical distance (V) and lateral distance (L) from the shoulder. In addition to these variables, H^2, V^2, L^2 and H*V, H*L, and V*L were also used as inputs to the regression equations, as these squred and interaction terms may have explained more variance. The regression models performed very well with a mean r^2 value of 94.6% and the greatest RMS % Error being only 5.4%.

The success of the regression equations developed by Freeman (2006) represents a promising step in the improvement of arm strength predictions. An important finding of this research was that such an accurate model could be developed only using three variables that are relatively easy to obtain: H, V and L. Though there were additional squared and interaction variables created from these that were important contributors to the equations, the relative ease of obtaining these measurements in a work place make this model very applicable in ergonomics and for potential use in digital human models. It should be noted that Freeman (2006) did not perform a validation using a sub-sample of subjects from his study, therefore these equations are not to be used for individuals, but rather for whole populations.

Potvin et al. (2010) presented data from a series of studies measuring female arm strengths in an attempt to develop more accurate predictive regression equations for maximal hand force capabilities in a variety of exertion directions and hand positions. The arm strength data from Freeman (2006) were utilized, and two more data collections were conducted in order to further supplement the collection of hand positions and strength data that could be used in the development of accurate regression equations. The total number of female subjects across all three data collections was 71 (Table 2.1).

Table 2.1: Subject characteristics from Potvin et al. (2010). The data were collected in three separate studies. Collection A is from Freeman (2006) and collections B and C were subsequent data collections using different hand postures, reaches and grips.

		Collection A			Collection B			Collection C			All Data			
	Age	20-29	30-39	40+	20-29	30-39	40+	20-29	30-39	40+	20-29	30-39	40+	All
Age (yrs)	Mean	23.1	33.6	48.3	23.8	32.0	47.8	-	35.3	48.4	23.5	33.4	48.3	34.1
	StDev	2.2	3.3	4.6	3.0	2.1	2.6	-	3.1	5.5	2.7	3.0	4.5	11.2
Height (m)	Mean	1.674	1.632	1.652	1.674	1.694	1.616	-	1.677	1.639	1.674	1.657	1.639	1.658
	StDev	0.071	0.064	0.033	0.078	0.040	0.042	-	0.040	0.037	0.074	0.060	0.037	0.062
Mass (kg)	Mean	64.8	67.0	68.3	63.2	60.3	61.2	-	80.0	70.7	63.8	67.3	67.7	65.9
	StDev	21.7	14.3	11.5	10.0	3.6	12.6	-	7.2	14.5	14.6	12.7	12.9	13.5
	n	10	10	9	20	5	5	0	3	9	30	18	23	71

All subjects produced maximal efforts in 6 exertion directions for each of the 28 hand locations. Initial analysis of the data shows that, across all 168 combinations of vertically oriented hand location (n=28) and directions (n=6), the equations explained 92.5% of the variance and had an RMS error of only 6.4 N, which was 7.2% of the overall mean maximal voluntary force (MVF) (89.8 N) and 3.9% of the maximum MVF range (164.4 N) (Figure 2.5). All linear (H, V, L), squared, cubed and interaction variables appeared in at least one equation, with V^2, H*V and L*V appearing in five of the six equations and L, H^2 and L^2 appearing in four (Table 2.2).

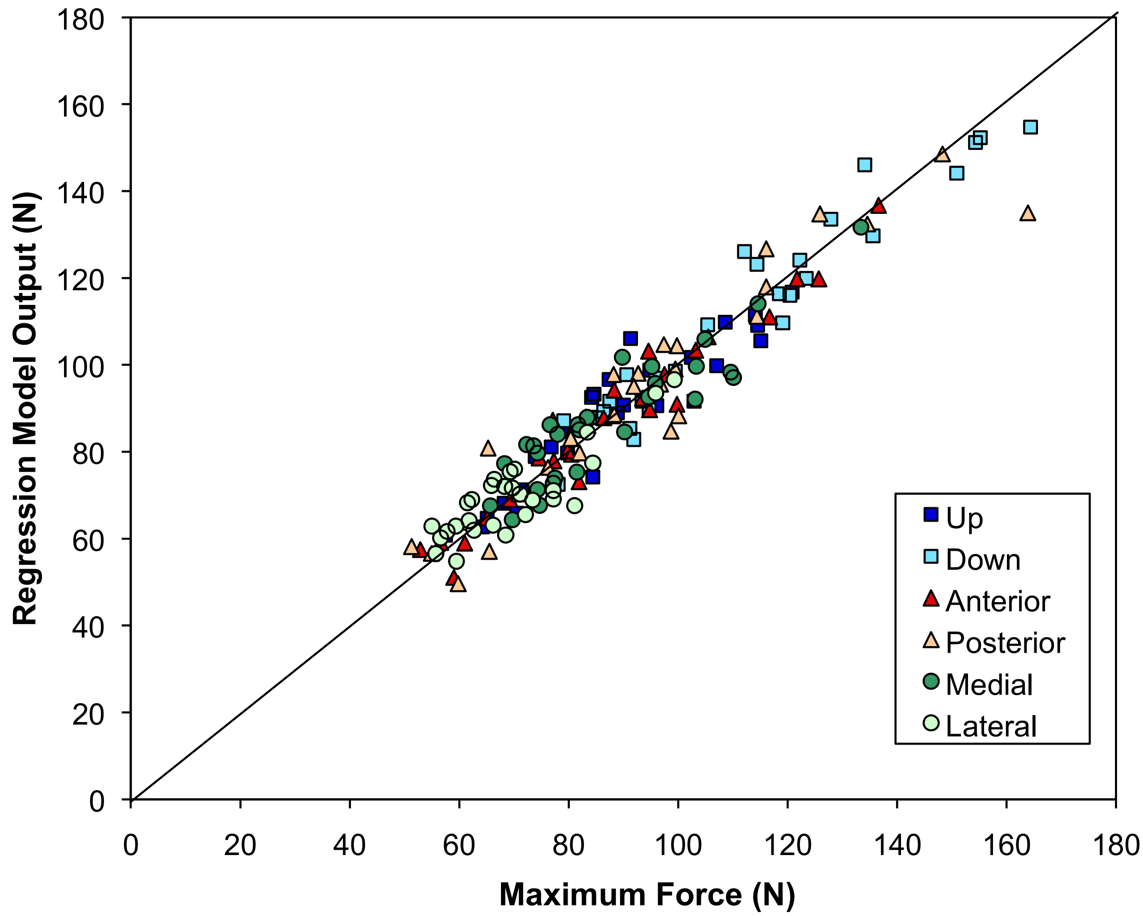


Figure 2.5: Regression results for each of the six equations (n=28 each) with the line of perfect prediction. Mean strength values are presented on the X-axis and the Regression outputs are shown on the Y-axis. The six equations explained 92.5 % of the variance and had an RMS error of 6.4 N. *Potvin et al. (2010).*

Table 2.2: Regression equation intercept and coefficients for each of the 6 directions (columns). Regression statistics are also presented for each equation (based on n = 28) and across all predictions (n = 168). V, H and L represent the vertical (V), horizontal (H) and lateral (L) location of the right hand with respect to the shoulder. Squared, Cubed and interaction terms based on V, H and L are also presented. *Potvin et al. (2010).*

	Direction						
Variable	**Up**	**Down**	**Push**	**Pull**	**Medial**	**Lateral**	
Intercept	100.7	140.2	96.2	98.9	95.1	55.4	
V		208.72	-43.06				
H						68.94	
L		-32.47	-31.34	-36.73		87.23	
V^2	91.93	-46.37	-126.96	-139.18	-123.58		
H^2	-161.70	-187.06	181.93	456.95			
L^2	-179.03	-169.46	-283.74	-391.98			
V^3		-604.21	147.23				
H^3				-496.04	-226.49	-315.53	
L^3			373.58	607.89	347.73		
H*L						-293.33	
H*V	-60.60	-220.40		-171.07	-61.24	45.40	
L*V	58.21	-127.77	32.08	-58.80	-179.04		
Regression Stats	**Up**	**Down**	**Push**	**Pull**	**Medial**	**Lateral**	**All**
Min MVF	57.5	78.1	52.9	51.3	65.7	55.0	51.3
Max MVF	120.8	164.4	136.6	163.9	133.4	99.3	120.8
Mean MVF	88.8	111.3	87.6	93.7	87.7	69.7	89.8
r	0.93	0.97	0.97	0.95	0.91	0.86	0.96
r^2	0.87	0.93	0.95	0.90	0.84	0.74	0.93
RMS Error	6.1	6.3	4.7	8.6	6.6	5.6	6.4
RMSE (%Mean)	6.9%	5.7%	5.4%	9.2%	7.6%	8.1%	7.2%
RMSE (%Max)	5.2%	4.1%	3.5%	5.8%	5.0%	5.8%	3.9%

In collections B and C, Potvin et al. (2010) also collected data in what are termed 2D and 3D force directions, where maximal efforts were made in a combination of the six exertion directions. An example of a 2D exertion would be simultaneously pushing up and forward, and an example of a 3D exertion would be simultaneously pushing up, forward and laterally to the right. In order for the 2D and 3D exertions to be considered valid, at least 90% of the resultant force had to have been in the required direction. Though this approach appears to be a promising start, the correlations and errors observed between the actual force and predicted force (R-square = 0.626, RMS Error = 17.1 N) were not as close as the uni-directional 1D exertions, and it was hypothesized that this may be due to the absence of arm posture data. In all these exertions, subjects were allowed to produce their maximal shoulder exertions using any desired arm posture. It is possible that by accounting for the average arm postures adopted by participants during these exertions, this may drastically improve both the 1D as well as the multi-dimensional shoulder strength predictions.

CHAPTER 3 - METHODS

3.1 – Measurement of Arm Strength and Posture

3.1.1 - Subjects:

Seventeen healthy female participants were recruited from the McMaster University community. All subjects were right-hand dominant and free from any recent lower or upper body acute injuries and/or chronic disorders. Descriptive anthropometric statistics are presented in table 3.1.

Table 3.1: Antrhopometrics of subjects included in study (n=17).

	Height (cm)	Weight (kg)	Age (yrs)
Mean	167.7	62.5	24.0
St.Dev.	6.8	10.9	1.8
min	152.5	52.2	21
max	183.5	95.3	26

Before commencement of the study, all participants were asked to read and sign a written consent form (Appendix B). All portions of this study had been reviewed and approved by the McMaster University Research Ethics Board before commencement of the data collection (Appendix E).

3.1.2 - Instrumentation and Data Acquisition:

A tri-axial load cell (500 lb. XYZ Sensor, Sensor Development Inc., Lake Orion, MI) was used to measure forces in all three orthogonal directions. A padded handle was screwed on to the load cell, which was then mounted on a horizontal length of slotted rail (80/20 Inc., Columbia City, IN). A telescoping padded pole was attached to the slotted rail apparatus and extended outwards to rest along the sternum of the participants, at their most comfortable location. This pole served to keep the sternum of the participants resting at a specific, constant distance away from the apparatus (Figure 3.1).

The tri-axial load cell was located on a rail with linear bearings fitted with a quick release handle, allowing for an easy transition between lateral (x-axis) locations. This horizontal rail was attached on both sides to two vertical length 80/20 slotted rails using a linear bearing system fitted with a quick release handle as well, allowing for easy movement in the vertical (y-axis) direction.

All force data were collected at 100 Hz with custom LabVIEW software (National Instruments, Austin TX) using a PC compatible computer and converted by a 12-bit A/D card (National Instruments, Austin TX).

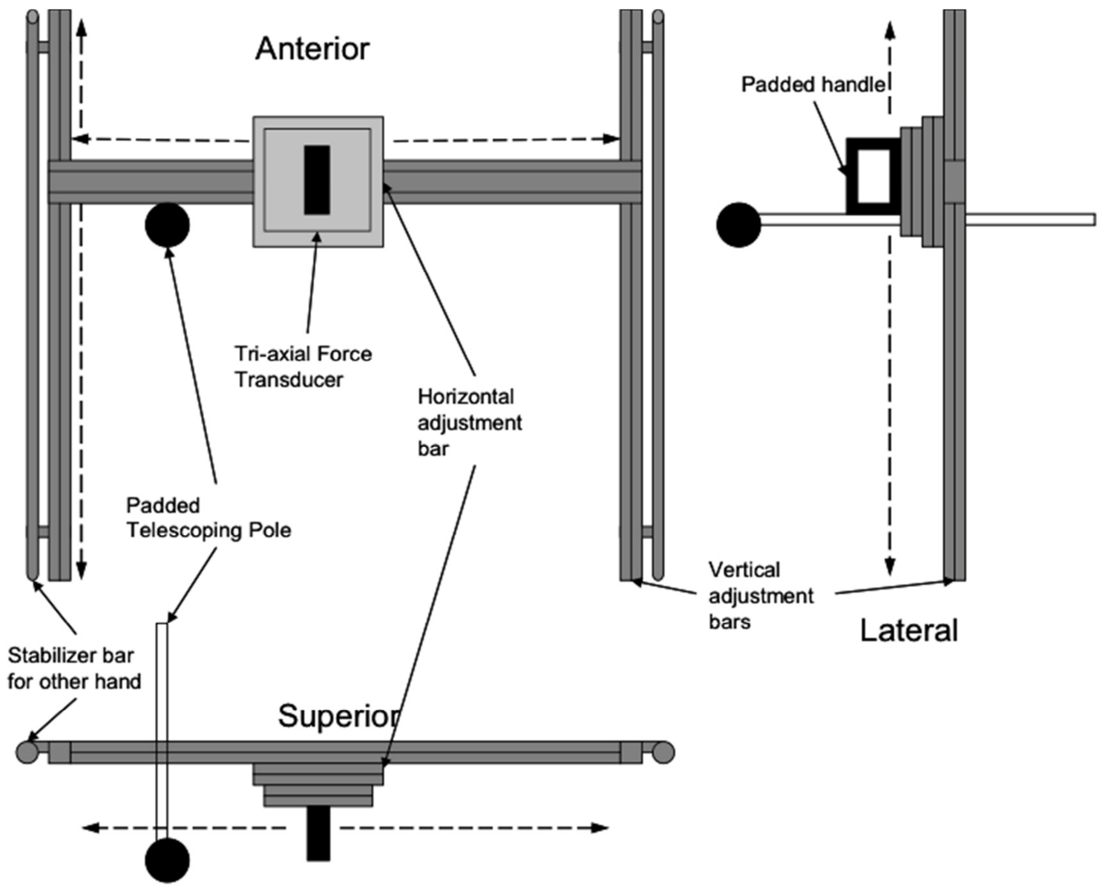


Figure 3.1: Anterior, superior and lateral views of the adjustable testing apparatus, including the tri-axial force transducer, handlebar and telescoping pole.

This LabView program also provided visual feedback to the subjects by displaying graphical information on the resultant direction of force application (Figure 3.2). The subjects' goal was to maximize the force amplitude (vertical axis on the feedback screen graph) of the appropriate colour-coded horizontal lines depending on the direction of the exertion, while keeping the resultant application of force in the required direction. If the force in the required direction of exertion was not at least 90% of the resultant force, the trial was discarded and re-collected.

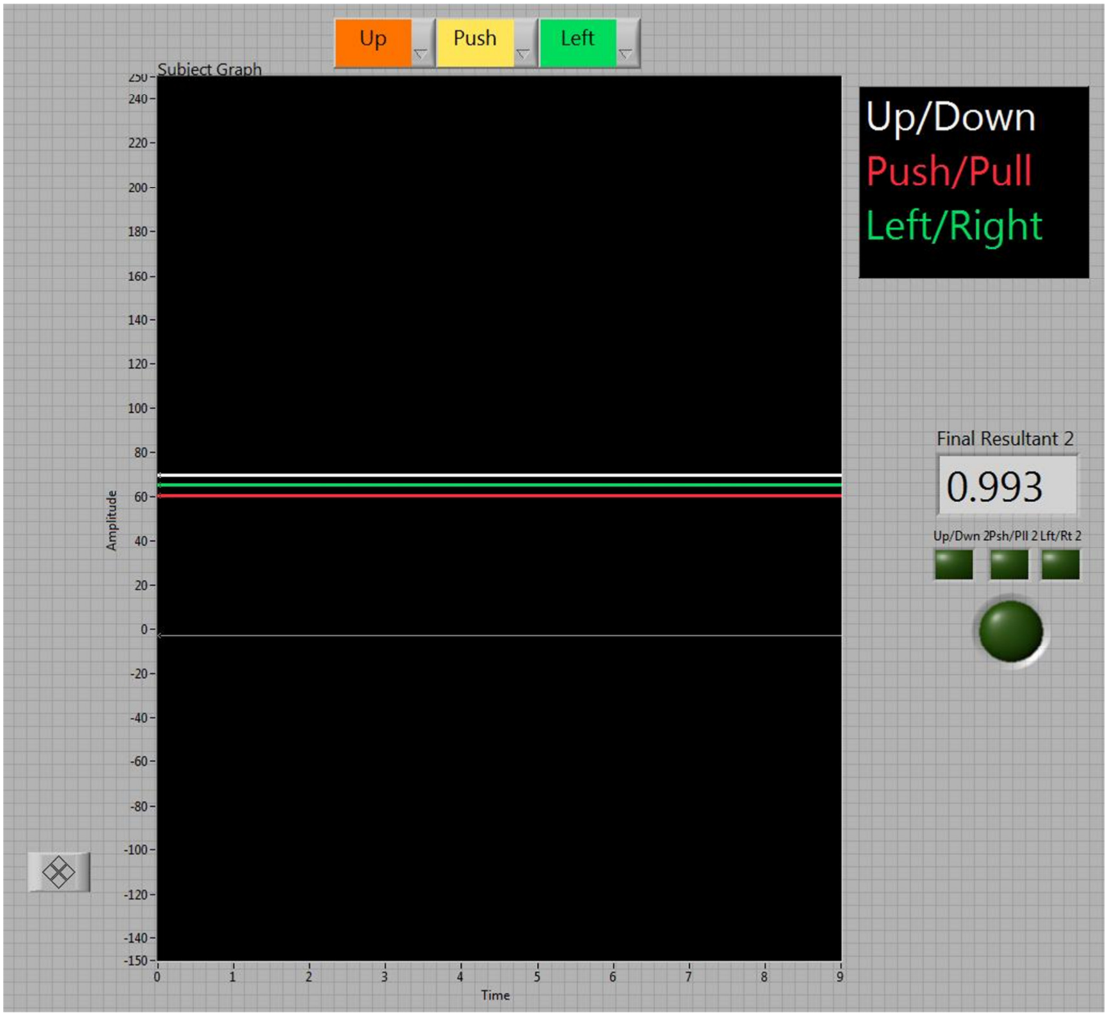


Figure 3.2: Screen capture of the visual display viewed by subjects during their exertions. An example of an up/push/left 3D exertion is shown, where the goal of the subjects was to match the 3 horizontal lines (equal force on all three axes) at their maximal force level. The white line represented the up/down force, the red line represented the push/pull force and the green line represented the left/right force.

Kinematic data were recorded at a sample rate of 50 Hz using ten cameras (Raptor-4. Motion Analysis Corporation, Santa Rosa, CA) and motion capture software (Cortex 1.3.0, Motion Analysis Corporation, Santa Rosa, CA). Eight reflective markers were placed on the subject, and one on the handlebar to determine the location of the upper limb segments and the handlebar in 3D space. As can be seen in Figure 3.3, three markers were placed on the shoulder, one superior to the acromioclavicular joint, one on the anterior deltoid and one on the posterior deltoid. Through palpation, the positions of the anterior and posterior deltoid markers were determined by estimating an artificial, conjoining line that ran through the humeral head. The elbow markers were fastened to a stick that protruded from a flexible elbow band. The base of this stick was placed over the lateral epicondyle of the elbow so that, in conjunction with a digital photograph taken of each subject's arm, the center of the elbow joint could be calculated. Despite using a motion capture system, the digital photograph was necessary to determine the exact location of the elbow with respect to the markers on the stick protruding from the elbow. The wrist markers were attached to a flexible wristband and placed over the radial and ulnar styloid processes. The axis system, as defined by the camera system, can be seen in Figure 3.3.

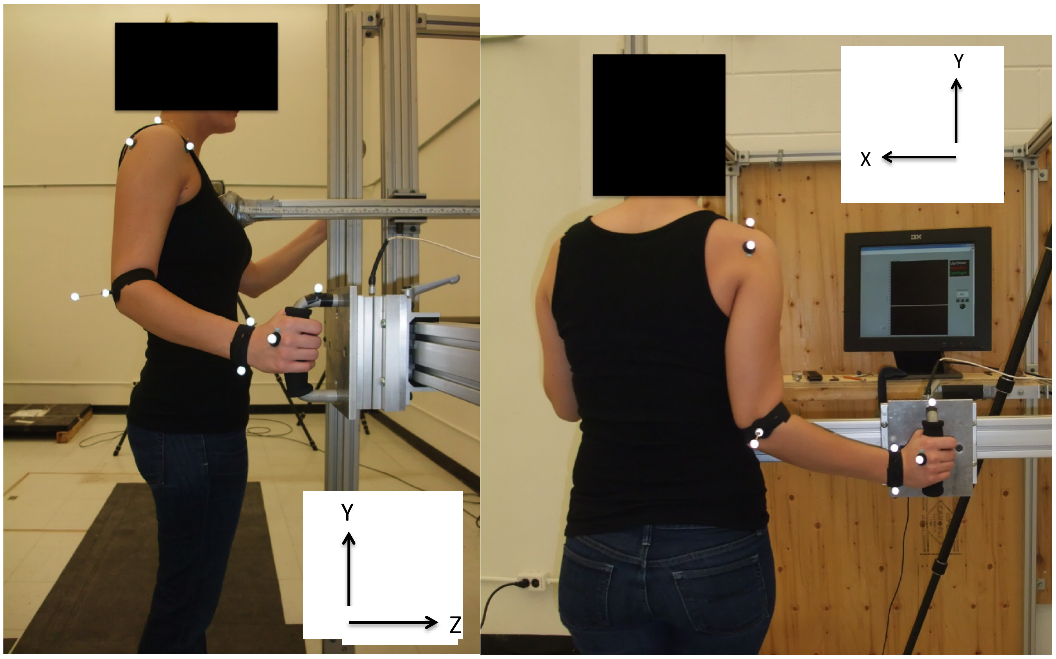


Figure 3.3: Lateral (left) and posterior (right) views of the experimental set up and reflective markers. The axis system defined by the camera system is also shown. Relative the subject shown above, the X-axis is in the left direction, Y-axis in the up direction and Z-axis in the forward direction.

3.1.3 - Experimental Procedures and Protocol

3.1.3.1 - Subject preparation and familiarization

Anthropometric measurements of height (cm), weight (kg), maximum arm reach (cm), shoulder width (cm), shoulder breadth (cm), shoulder height (cm) and umbilicus height (cm) were taken in order to determine the specific hand locations for each subject. The anthropometric measurements were defined using the following conventions: maximum arm reach was the distance from the acromion process of the scapula to the 3rd metacarpophalangeal (MCP) joint; shoulder width was the distance from the left acromion process to the right acromion process; shoulder breadth was the linear distance from the anterior to the posterior shoulder; and shoulder height was measured from the acromion process to the ground. All anthropometric information was entered into a spreadsheet and specific hand locations were calculated based on the measurements of the participant.

Before commencement of the strength trials, the subjects were taken through a familiarization protocol in which they produced forces in one of the eight pre-selected hand locations with direct feedback from a member of the research team. All three types of directional exertions were practiced in the familiarization session to ensure the participants understood the concept of the one-dimensional 1D (e.g. push), 2D (e.g. push and up) and 3D exertions (e.g. push, up and lateral). Forces were practiced in a randomized order, therefore the subjects did not necessarily practice in every exertion direction. In terms of the axis system, the X-axis represented the medial(+)/lateral(-) dimension; the Y-axis represented the up(+)/down(-) dimension; and the Z-axis represented the push(+)/pull(-) dimension (seen in Figure 3.3).

3.1.3.2 – Strength Trial protocol

Once the subjects were comfortable with the task, they commenced the MVC strength trials. MVC exertions were performed at eight hand locations defined by both the horizontal angle of the arm (0°, 45° and 90°) (Figure 3.4) and the vertical height relative to the body (umbilicus, shoulder, and overhead heights). The eight hand locations tested in this thesis were: Umbilicus at 0°, Umbilicus at 45°, Umbilicus at 90°, Shoulder at 0°, Shoulder at 45°, Shoulder at 90°, Overhead at 0° and Overhead at 45° (Figure 3.5). The order in which these hand locations were presented was randomized between subjects. All hand locations were set based on the unique anthropometrics of each subject and the distance of the hand from the shoulder was calculated to be 80% of their maximum arm reach. The height of the overhead exertions was set by the arm maintaining a 45° vertical angle from the horizontal plane of the shoulder.

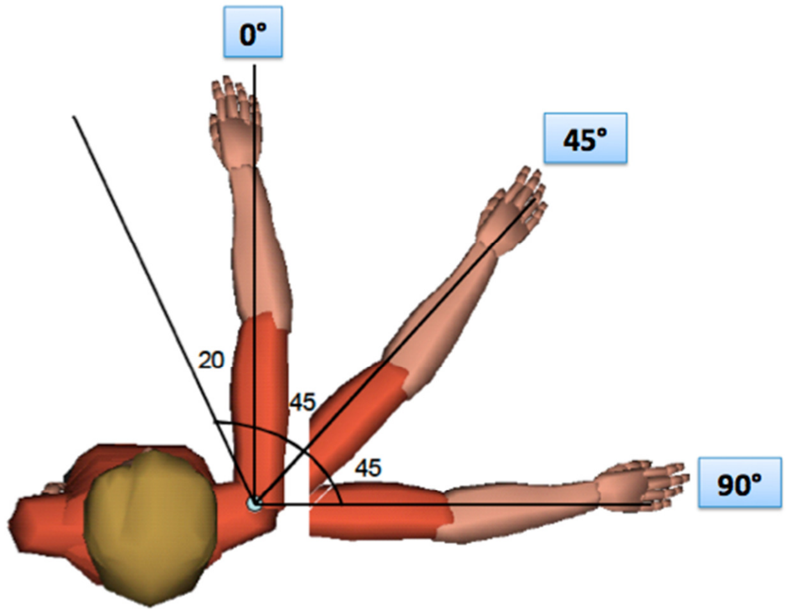


Figure 3.4: Overhead view of shoulder angles. 0° represents the arm fully flexed at the shoulder in the sagittal plane, from the right shoulder. 90° represents the arm in full abduction, or 90° rotated from the 0° position. 45° would be directly inbetween the 0° and 90° angles. *Freeman (2006).*

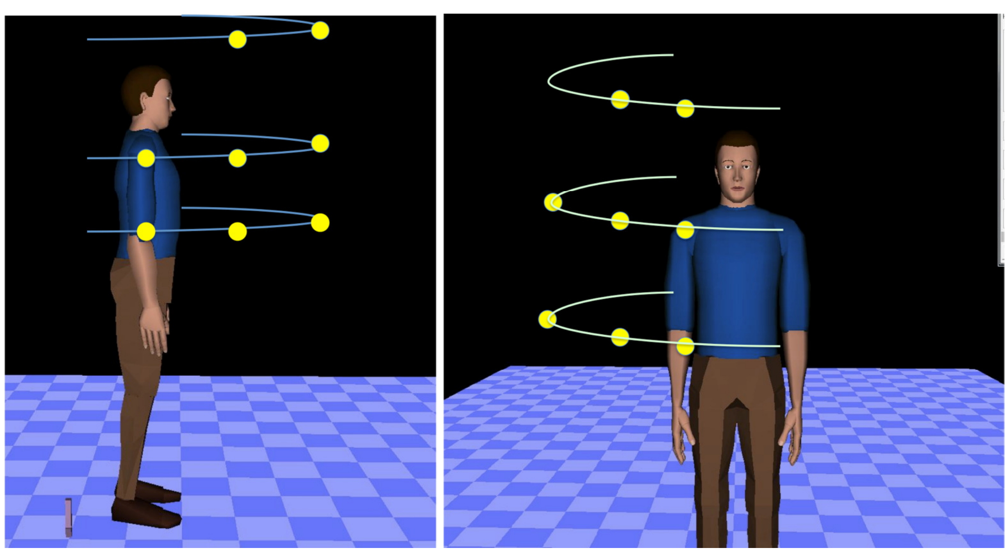


Figure 3.5: Graphical representation of the 8 hand locations tested.

At every hand location, each subject performed twenty-six 1D, 2D and 3D exertion directions in a randomized order (Table 3.2). For each maximal voluntary contraction (MVC), the subjects ramped their application of force over two seconds to their maximum, held for two seconds, and then ramped down in two-seconds. Subjects then had one minute of rest before starting the next trial. In total, approximately 240 exertions were completed during the study (8 locations x 26 exertions per location = 208 exertions, plus an allowed 32 recollected trials per subject). In order to complete these exertions with adequate rest between trials, the entire protocol took place in four, 1-hour testing sessions. Within each testing session, two randomized blocks of hand-locations were tested in all 26 exertion directions for a total of 52 MVCs per session. There was at least three days of rest between subsequent testing days. In sessions 2, 3 and 4, subjects started the testing immediately upon arrival, forgoing the familiarization session.

Table 3.2: The 26 exertions in 1D, 2D and 3D directions for each of the 8 hand locations.

	1-D Directions		
1	Up		
2	Down		
3	Push		
4	Pull		
5	Left		
6	Right		
	2D Directions		
7	Up	Push	
8	Up	Pull	
9	Up	Left	
10	Up	Right	
11	Down	Push	
12	Down	Pull	
13	Down	Left	
14	Down	Right	
15	Push	Left	
16	Push	Right	
17	Pull	Left	
18	Pull	Right	
	3D Directions		
19	Up	Push	Left
20	Up	Push	Right
21	Up	Pull	Left
22	Up	Pull	Right
23	Down	Push	Left
24	Down	Push	Right
25	Down	Pull	Left
26	Down	Pull	Right

3.1.4 – Data Analysis

The independent variables in this study were hand location and force direction. The resultant of the peak force that was observed in each trial, based on a one-second moving average, was taken to be the maximal strength of that subject for that trial. The dependent variables were the maximum force as well as the 3D locations of the shoulder, elbow, wrist and hand. Based on these position data, upper arm angles and 3D moment arms, from the force vector to the shoulder and elbow joints, were computed and used as dependent variables as well.

Joint locations were calculated using the 3D coordinates of the eight on-subject reflective markers. Shoulder location was assumed to be the mid-point between the markers on the anterior and posterior shoulder. The wrist location was assumed to be the mid-point between the markers on the radial and ulnar styloid processes. In order to determine the location of the elbow, a photograph of each subject's arm was taken during the data collection so that the elbow location could be digitized, given the known distance and orientation of the two markers on the stick. Rather than just approximating some constant distance down the axis of the two markers, this individual photo digitization method allowed for more accuracy and control over errors due to differing subject arm sizes. An example of a photograph used in the elbow location calculation can also be seen in Figure 3.6. As the distance between the two markers on the elbow stick was a constant (53.8 mm), the location of the elbow (yellow dot over elbow) could be approximated using a scaling method.

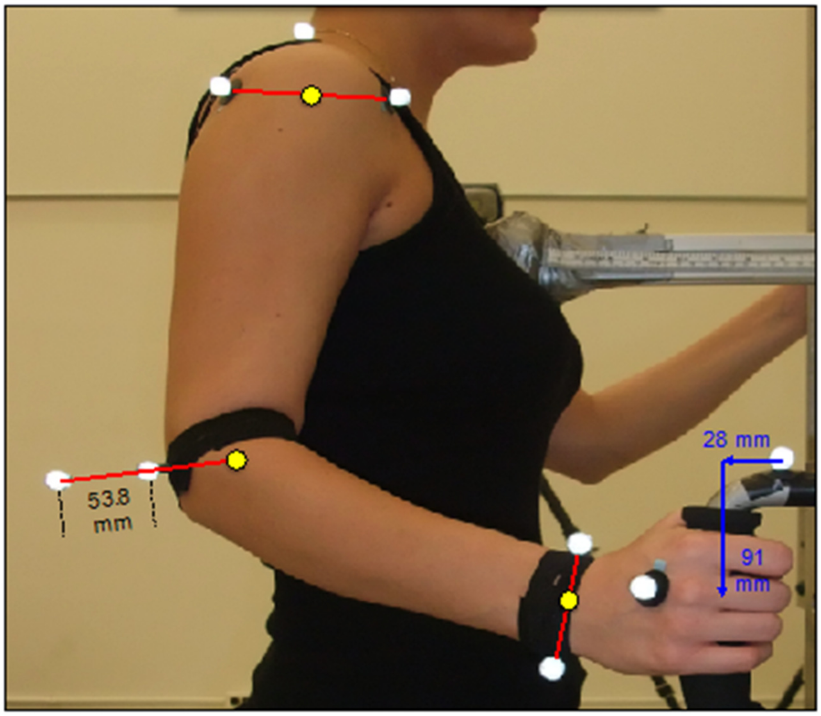


Figure 3.6: Lateral view of arm with kinematic markers attached. The midpoint between the anterior and posterior shoulder markers was taken to be the shoulder location, and the midpoint between the ulnar and radial wrist markers was taken to be the wrist location. The elbow location was approximated based on the known distance between the 2 markers on the stick protruding from the elbow and a photograph taken of each subject's arm. The centre of the handlebar was determined by translating the handlebar marker down the y-axis by 91mm, and back in the z-axis by 28mm.

The hand location was approximated based on the location of the marker on the handlebar, which was translated down the vertical y-axis by 91 mm, and horizontally backwards along the Z-axis by 28 mm in order to estimate the middle of the bar (see Figure 3.6). Corrections were made so that the hand location represented the point of force application on the surface of handlebar. Therefore, there were eight different corrections applied to the position of the hand based on exertion direction in order to represent the exact point of force application (Figure 3.7).

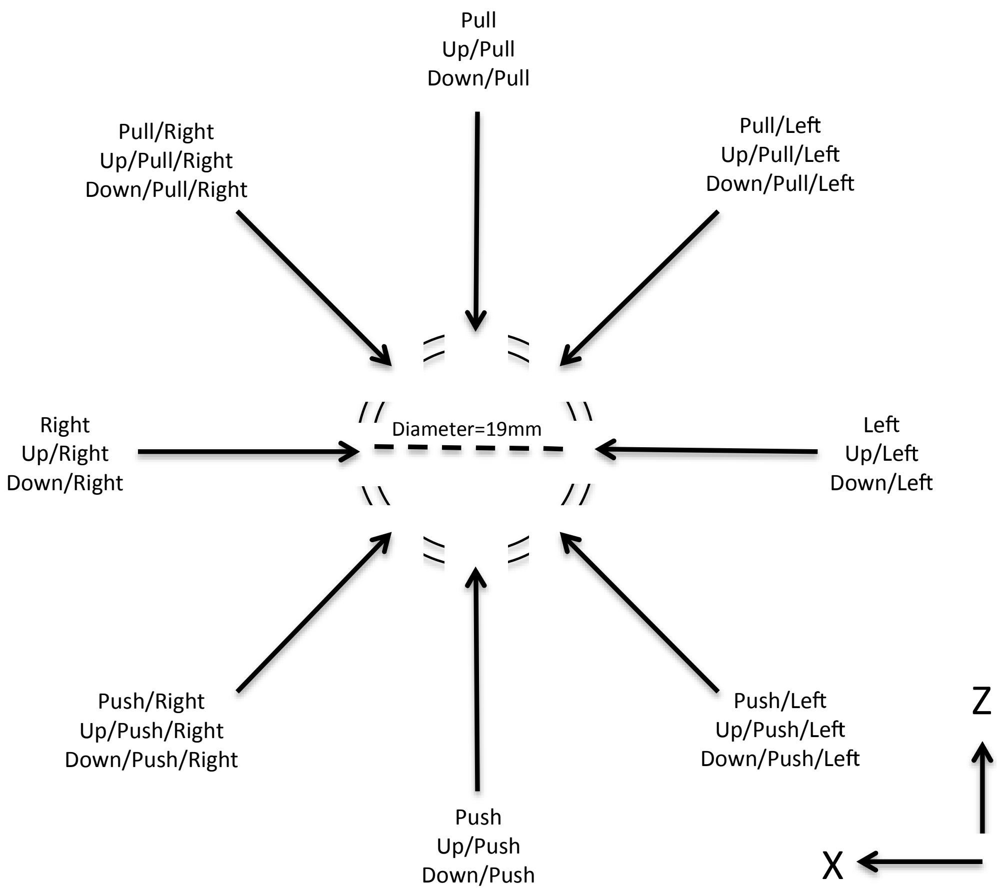


Figure 3.7: Cross-section through the middle of the handlebar, looking down the Y-axis. Once the 3D location of the hand was determined based on the handlebar 3D location, a correction was made in order to move the point of force application from the middle of the handlebar to one of eight points on the edge of the bar, depending on exertion direction. No corrections were applied to the up and down 1D-directions as the force was assumed to be evenly distributed around the bar.

The three arm angles were determined based on the locations of the upper limb joints. Elbow flexion angle was calculated by taking the dot product of the forearm (line joining the calculated wrist and elbow) and the upper arm (line joining the calculated elbow and shoulder). When fully extended, the elbow was at 180°, and elbow flexion caused a decrease in angle. The shoulder angles were calculated according to the conventions of the 3DSSPP software (The University of Michigan Center for Ergonomics, 2006). Vertical angle was defined as the angle subtended between the upper arm and a vertical vector dropped from the shoulder down the y-axis. The horizontal angle was defined as the angle made by the upper arm on the XZ plane (Figure 3.8). Therefore, a horizontal angle of 0° would mean the upper arm was abducted laterally (point in the –X direction) and a horizontal angle of 90° would mean the upper arm was flexed forward (pointing in the +Z direction).

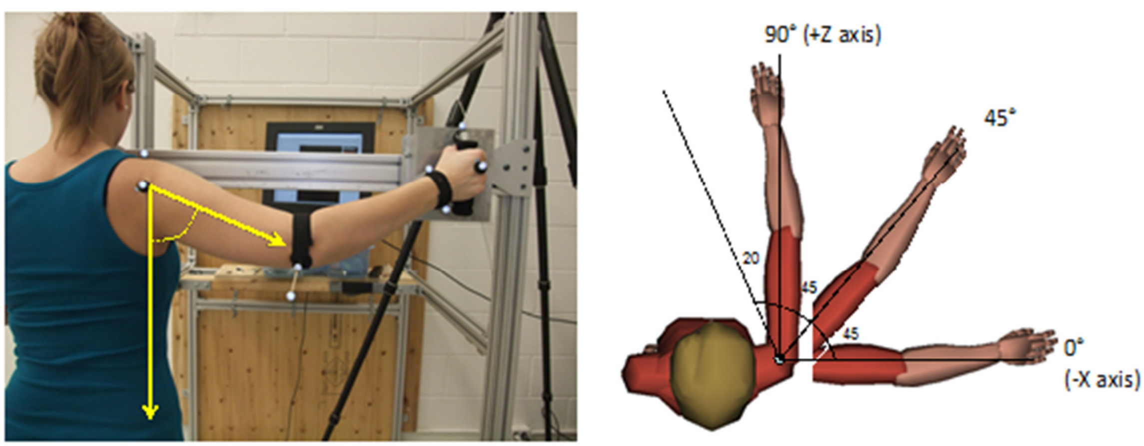


Figure 3.8 Vertical (left) and horizontal (right) shoulder angles. Note that for the horizontal shoulder angles, the convention is different from the angles used to define hand location angles (see Figure 3.4).

The remaining independent variables that had to be calculated were the force unit vectors and 3D moment arms. A force unit vector was calculated for each effort as it represented the direction cosines of the resultant force. The 3D moment arms, of the resultant force to the shoulder and elbow joints, were then calculated using the cross product of the unit vectors and the 3D radius vectors. These 3D radius vectors define the x, y and z displacement from the point of application at the hand to the shoulder and to the elbow.

<u>3.1.5 – Statistical Analysis</u>

Descriptive statistics such as the means, standard deviations and coefficients of variation (CV) of these peak forces were determined for each combination of hand location (n=8) and force direction (n=26), for a total of 208 conditions.

3.2 – Prediction of Arm Strength with Regression Equations

<u>3.2.1 – Comparison of Regression models with and without postural information</u>

Inputs pertaining to the arm were used in the development of two versions of multivariate regression equations to predict average strength in all 26 of the 1D, 2D and 3D exertion directions for each of the 8 hand locations (Appendix C, n=208). The independent variables were all linear in nature (i.e., did not include squared, cubed or interaction terms) and consisted of group averages of: unit vectors (X, Y, Z), hand locations (X, Y, Z), elbow flexion angles, shoulder horizontal angles, shoulder vertical angles, resultant shoulder 3D moment arms and resultant elbow 3D moment arms (M_{ALL}, Table 3.3).The regression analysis was run using a stepwise approach (F = 4.0 to enter) using StatsView (SAS Institute Inc., 1997).

A unique aspect of the current research, compared to Potvin et al (2010), is that data included the elbow location, elbow angle and shoulder angles. To test the contribution of this added information, to the strength predictions, a multivariate regression equation was also developed with only the unit vectors, hand location and shoulder 3D moment arms included as independent variables (M_{NP}, Table 3.3).

Table 3.3: Dependent and independent variables for the regression equations. M_{ALL} includes elbow terms and arm angle information that would not otherwise be known without kinematic tracking of the arm segments (M_{NP}). n=208 for both equations.

Dependent Variable	Independent Variables	
	M_{ALL}	**M_{NP}**
Resultant Strength	Unit Vector (Up/Down)	Unit Vector (Up/Down)
	Unit Vector (Push/Pull)	Unit Vector (Push/Pull)
	Unit Vector (Med./Lat.)	Unit Vector (Med./Lat.)
	Hand Location (X)	Hand Location (X)
	Hand Location (Y)	Hand Location (Y)
	Hand Location (Z)	Hand Location (Z)
	Shoulder 3D MA	Shoulder 3D MA
	Elbow 3D MA	
	Elbow Flexion Angle	
	Shoulder Horiz. Angle	
	Shoulder Vert. Angle	

3.2.3 – Regression Equation Interpolation

In order to determine the effects of interpolating between hand locations tested in this thesis, a graphical approach was undertaken to ensure there was somewhat of a continuous progression in either the increase or decrease of force with a change in arm angle at each of the three hand location heights. M_{NP} was used, with only the hand location and shoulder moment arms as inputs, as it was difficult to predict where the elbow would be located at the interpolated angles with satisfactory accuracy. For each of the hand location heights, the average H, V and L's were found and the following hand locations were estimated: Umbilicus, Shoulder and Overhead at 11.25°, 22.5°, 33.75°, 45°, 56.25°, 67.5°, 78.75° and 90°. Each of the calculated H, V and L values at these new locations were inputted into M_{NP} and the predicted strengths were plotted to determine if there was a continuous trend visible between experimentally measured hand locations and hand locations somewhere within the reach envelope, not included in the study.

3.2.4 – Statistical Analysis

Several regression equations were developed for investigative purposes and to infer what information or methodological approaches yield the most powerful predictive models. In determining a model's performance, a correlation of $r > 0.9$ (r^2 >81%) was considered a good prediction, r = 0.70–0.89 (r2 = 49%-80%) a moderate prediction, and r = 0.50–0.69 (r^2 = 25%-48%) a low or poor prediction (Vincent, 2005).

3.3 – Comparison of Empirical Arm Strength with the 3DSSPP Software

A study was conducted to compare the empirical results to the 3DSSPP arm strength predictions. A collection of 1D-maximal strengths from 44 hand locations (36 from Potvin et al. (2010), and 8 from this thesis) were used in a comparison against the corresponding 50-percent capable (mean) strengths from a 3DSSPP manikin of matching anthropometrics.

3.3.1 Subjects

Potvin et al. (2010) presented data from three separate data collections totaling 71 subjects (Table 2.1 in Literature review). The empirical data collected in this thesis (termed Collection D) added 17 more subjects to the pool of data for a total of 88 subjects.

3.3.2 - 3DSSPP strength prediction data collection

The analysis was performed using the most recent version of the software, 3DSSPP 6.0.4 developed by the University of Michigan's Center for Ergonomics (2010). A female model was used and the anthropometrics were scaled to the average height and weight of the 71 subjects from Potvin et al. (2010), and 17 subjects of this thesis for the respective hand location comparisons. The female mannequin was placed into a neutral standing posture and using the posture locking function within 3DSSPP, all body segments were constrained so only the arm could move. This was similar to the postural constraints for the empirical data that will be used for the comparison.

The 3DSSPP software contains a posture prediction component that predicts the posture that will be obtained by a human based on the location of the hands. The location of the hand is defined by three coordinates; H (horizontal distance from the frontal plane of the body), V (vertical distance from floor) and L (lateral distance of hand from the midline of the body). Once these three coordinates were entered, the hand and arm adopted the posture that was predicted to be achieved by a real human, and biomechanical analyses could be performed for the forces exerted by the hands, and the equal and opposite forces acting on the female mannequin.

In order to determine the hand locations to enter into 3DSSPP, the average locations of the right hand, relative to the shoulder, in the Potvin et al. (2010) study and the current thesis had to be converted to the 3DSSPP convention, which takes H, V and L with respect to the ground projected under the mid point between the ankles. Therefore, the H, V, and L of the 3DSSPP manikin's shoulder were, respectively, added as biases to the horizontal, vertical and lateral displacement of the hand with respect to the shoulder (from the studies) to obtain the converted coordinates. These hand positions were entered into 3DSSPP and the predicted posture was obtained. No postural manipulations were made to the manikin as it was assumed that most ergonomists would use the predicted posture provided by 3DSSPP without further manipulation. For each hand location, the maximal force acceptable to a 50th percentile female (ie. population mean) was determined for each of the six 1D exertion directions for each of the 44 hand locations where arm strength values were measured. Using the percent capable values, the hand load (force) was increased iteratively by 0.5 N until one of the three shoulder strengths or wrist strengths, or the single elbow strength variable dropped below 50% capable for the female manikin described above. The highest force that was obtained before the percent capable dropped below 50% was taken as the maximum capable force for that particular force direction and hand location combination. This iterative process, to determine maximal arm strength capabilities, was repeated for all combinations of 44 hand-locations and six 1D directions (264 combinations) between 3DSSPPs arm strength predictions and the empirical arm strength data (Figure 3.9 and Appendix F).

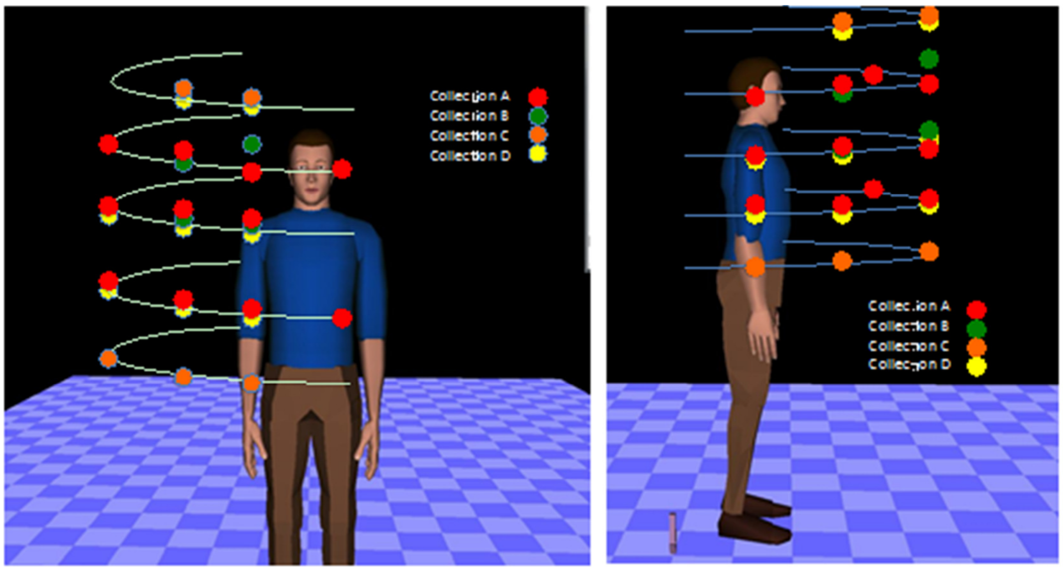


Figure 3.9 Graphical representation of the hand locations previously tested (Collections A, B, and C) and collected in this thesis (Collection D). The maximal 1D forces recorded at these hand locations were compared to the 3DSSPP outputs for the same hand locations.

3.3.3 - Data Analysis

After all 3DSSPP maximal predicted strengths were determined, a Pearson's correlation was used to compare them to the empirical arm strength values from the current study and Potvin et al. (2010) (Microsoft Excel, 2010). The explained variance (R-square), RMS error and absolute error between the measured strength values and the 3DSSPP predictive outputs was evaluated within each of the six exertion directions, and each of the hand heights, to determine the validity of the

3DSSPP outputs. The most common limiting joints and muscle effects were also evaluated to determine what the most common limiting joint was at the hand locations and exertion directions tested . As with the equations developed in 3.2 of this thesis, a correlation of $r > 0.9$ was considered a good prediction, $r = 0.7 – 0.89$ a moderate prediction, and r 0.5 – 0.69 a low or poor prediction (Vincent, 2005).

CHAPTER 4 - RESULTS

4.1 – Strength Data

4.1.1 – Hand Location

All individual strength data were pooled within each of the eight hand locations and presented in Appendix C.1 Overall, when averaged across exertion direction, the greatest average strength was found to be at Shoulder height at 0° (77.7 ± 34.0 N) and Umbilicus height at 0° (77.7 ± 36.3 N). Alternatively, the hand location with the lowest overall strength was the Shoulder height at 90° location (56.4 ± 27.8 N) (Figure 4.1).

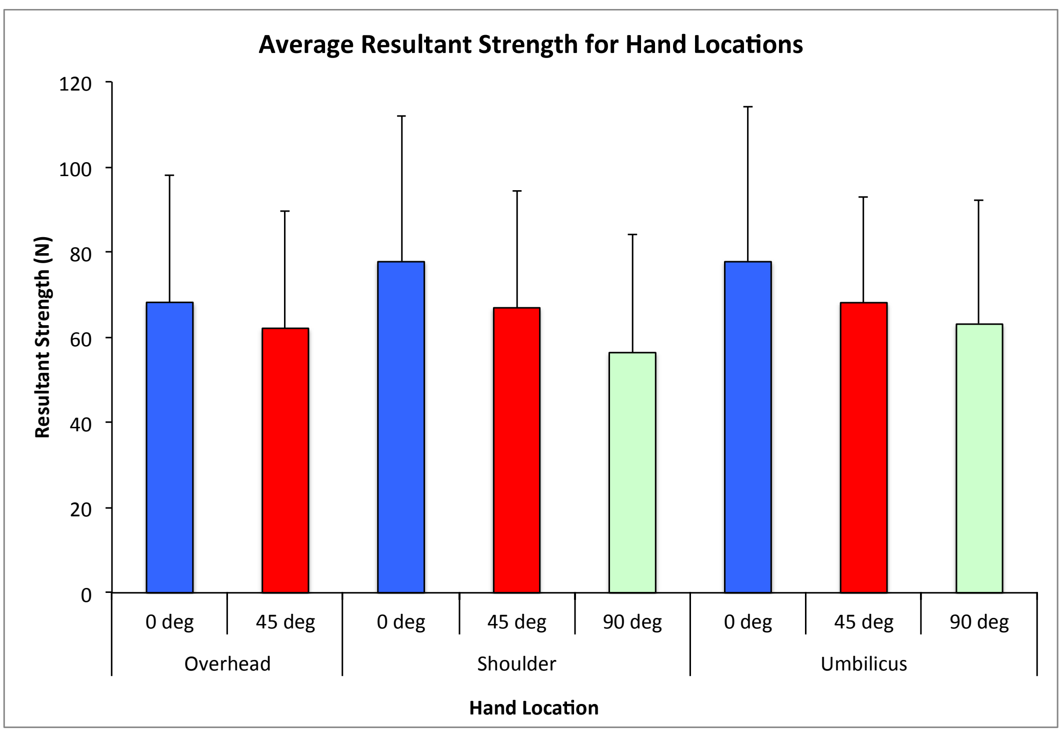


Figure 4.1: Mean resultant strengths for each of the individual hand locations, pooled across exertion directions (n=26). Error bars indicate standard deviations. Colours indicate angle.

4.1.2 – Exertion Directions

Average strength for each combination of hand location and effort direction are presented in Figure 4.2 and Appendix C.1. A general trend can be seen across all hand locations in that the strongest directions tended to be those in-line with the arm. At the 0° shoulder angle, there was a trend towards increased strength in the push and pull directions. At the 0° overhead and shoulder locations, pull exertions involving a down component tended to be the strongest. At the Umbilicus 0° hand location, the strongest exertion directions were generally in the pull directions, especially when there was an upward component to the pull. At the 45° shoulder angle, there was a shift in the general orientation of the strengths by 45° to remain in line with the arm. At the overhead level, the strongest directions were in the up/push/lateral and down/pull/medial directions. For both the shoulder and umbilicus 45° locations, the strongest directions were in the pull/medial directions. At the 90° shoulder angle, there was once again a shift in the orientation of the strengths by 45° laterally. At this fully abducted shoulder angle, the strongest exertions tended to be in the medial/lateral direction, again in line with the arm.

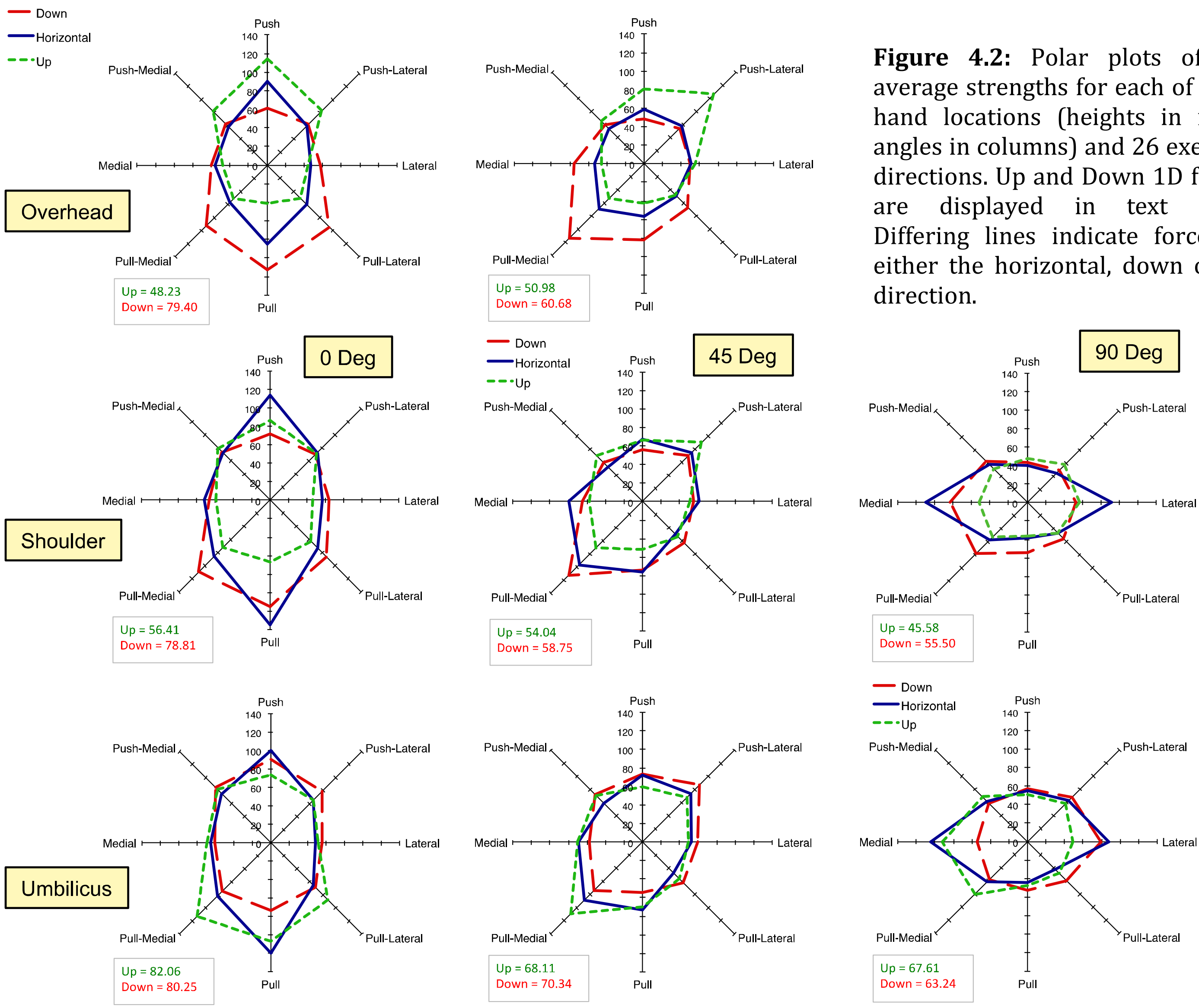


Figure 4.2: Polar plots of the average strengths for each of the 8 hand locations (heights in rows, angles in columns) and 26 exertion directions. Up and Down 1D forces are displayed in text form. Differing lines indicate forces in either the horizontal, down or up direction.

4.1.3 – Coefficients of Variation

Individual coefficients of variation (CV) were calculated for each of the 208 conditions tested (Table 4.1). Amongst hand locations, the Umbilicus 45 deg location had the lowest average CV at 29.9% and the Umbilicus at 0 deg location had the highest average at 38.4%. In terms of the 26 exertion direction means, the highest CV was seen with the 1D-down direction (43.2%) and the lowest CV was observed at the 3D-up/pull/right condition (27.0%).

4.1.4 – Kinematic Analysis

The hand location, relative to the shoulder, for both the Shoulder and Umbilicus at 90° conditions were slightly in front of the shoulder during the exertions, but only by 8.0 ± 3.0 cm and 7.0 ± 3.0 cm, respectively (Figure 4.3) . When examining the variance of the 3D location of the shoulder during the trials, the average resultant within-subject standard deviations were found to range from 1.9 cm to 2.9 cm across hand locations, with the lowest mean deviation occurring at the Shoulder at 45° condition and the greatest amount occurring at the Overhead at 0° condition (Figure 4.4).

Table 4.1: Coefficients of Variation (CV) for the 208 condition means in this thesis (8 hand locations x 26 exertion directions). For each hand location (columns), the maximum and minimum CV's are highlighted in green and pink, respectively. The overall mean represents the average mean across all 208 conditions. The maximums and minimums for overall hand location and direction means are also highlighted in green (max) and pink (min).

		Coefficients of Variation								
		Overhead		Shoulder			Umbilicus			Direction
Dim	**Direction**	**0 deg**	**45 deg**	**0 deg**	**45 deg**	**90 deg**	**0 deg**	**45 deg**	**90 deg**	**Mean**
1	Up	41.4%	35.9%	36.5%	35.8%	41.4%	**53.3%**	42.7%	39.3%	40.8%
1	Down	41.2%	38.6%	**42.4%**	44.7%	35.6%	47.9%	**49.3%**	46.4%	**43.2%**
1	Push	39.4%	33.7%	34.4%	34.3%	30.2%	46.2%	28.3%	39.8%	35.8%
1	Pull	38.9%	35.2%	40.6%	38.6%	33.5%	52.3%	38.2%	28.9%	38.3%
1	Left	29.5%	27.0%	36.4%	**50.9%**	51.0%	41.5%	38.4%	**49.5%**	40.5%
1	Right	34.8%	30.8%	33.2%	41.2%	**55.9%**	26.4%	30.6%	48.2%	37.7%
2	Up/Push	29.1%	**46.0%**	32.9%	29.2%	40.6%	44.5%	31.6%	31.1%	35.6%
2	Up/Pull	24.3%	23.3%	33.5%	30.7%	24.3%	48.1%	28.7%	39.0%	31.5%
2	Up/Left	28.5%	36.3%	36.1%	29.1%	28.1%	43.0%	35.1%	36.5%	34.1%
2	Up/Right	26.3%	23.6%	**24.0%**	30.4%	30.0%	30.0%	26.0%	30.4%	27.6%
2	Down/Push	33.6%	21.7%	31.3%	27.3%	30.3%	41.8%	27.5%	38.1%	31.4%
2	Down/Pull	30.9%	44.1%	36.4%	37.1%	34.7%	35.8%	23.9%	36.6%	34.9%
2	Down/Left	28.3%	36.8%	36.7%	29.5%	43.9%	42.3%	33.2%	35.0%	35.7%
2	Down/Rigt	40.1%	22.3%	40.7%	25.2%	28.0%	32.5%	28.6%	42.3%	32.5%
2	Push/Left	**18.2%**	23.4%	31.0%	25.5%	37.0%	35.2%	25.0%	34.7%	28.8%
2	Push/Right	26.4%	27.1%	30.5%	23.7%	27.0%	33.7%	25.2%	41.7%	29.4%
2	Pull/Left	24.8%	34.5%	35.3%	39.8%	35.3%	37.3%	35.5%	42.5%	35.6%
2	Pull/Right	34.0%	35.1%	30.0%	25.6%	34.8%	35.5%	**19.1%**	**26.1%**	30.0%
3	Up/Push/Left	24.7%	**16.4%**	29.7%	30.0%	28.0%	45.5%	26.3%	36.4%	29.6%
3	Up/Push/Right	**46.6%**	38.5%	30.4%	36.7%	32.7%	25.7%	28.8%	37.7%	34.6%
3	Up/Pull/Left	31.0%	33.4%	36.0%	29.4%	**22.2%**	37.8%	28.1%	39.5%	32.2%
3	Up/Pull/Right	20.2%	18.8%	31.5%	**22.4%**	27.0%	37.9%	22.1%	35.9%	**27.0%**
3	Down/Push/Left	20.8%	28.0%	32.5%	27.0%	28.3%	39.4%	25.7%	39.4%	30.1%
3	Down/Push/Right	30.5%	27.4%	28.3%	31.9%	43.3%	**24.5%**	33.4%	30.7%	31.3%
3	Down/Pull/Left	29.7%	34.7%	39.9%	35.6%	33.5%	32.9%	25.3%	36.0%	33.4%
3	Down/Pull/Right	24.2%	28.1%	29.6%	28.6%	32.9%	27.9%	22.0%	30.1%	27.9%
	Hand Location Mean	30.7%	30.8%	33.8%	32.3%	34.2%	**38.4%**	**29.9%**	37.4%	
	Overall Mean	33.4%								

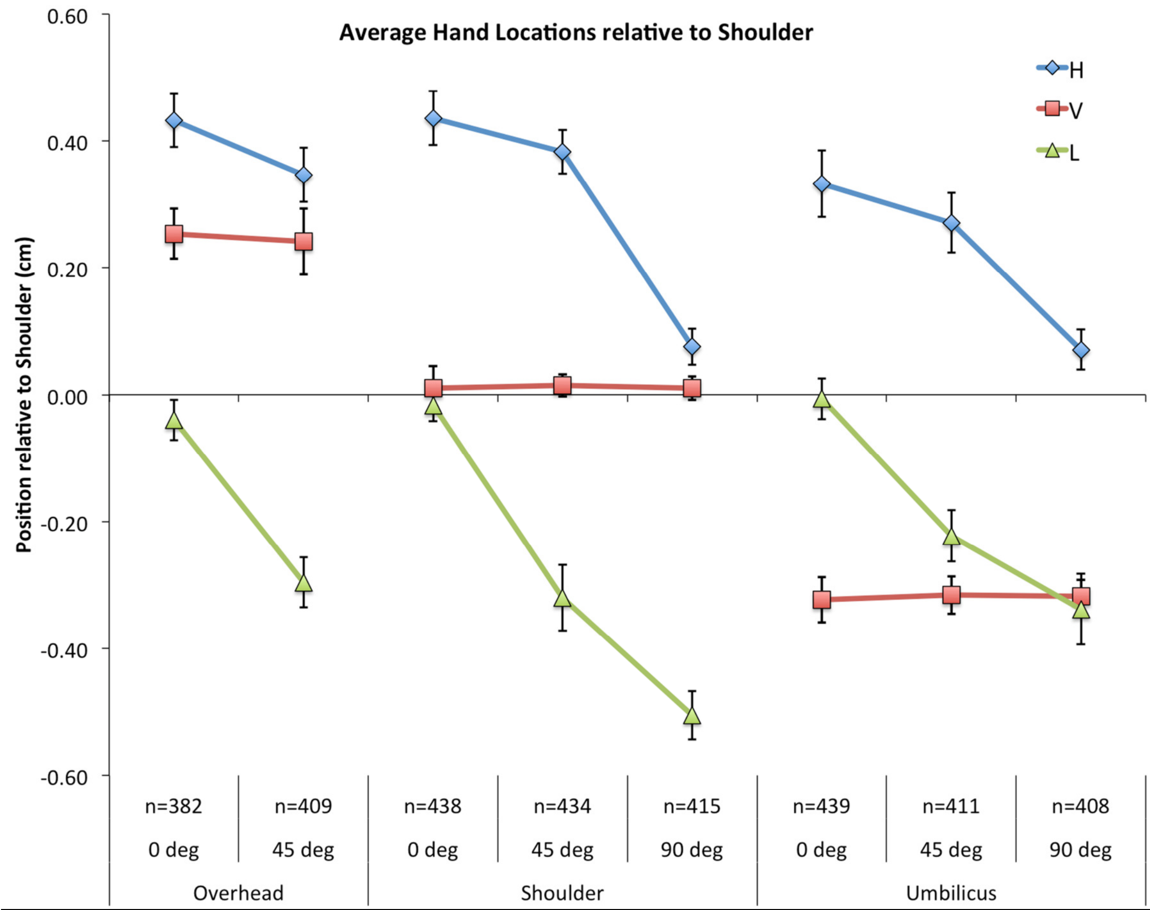


Figure 4.3: Average horizontal (H), vertical (V) and lateral (L) locations of the hand relative to the shoulder. Error bars indicate standard deviations between subjects. The number of trials in each hand location are also presented.

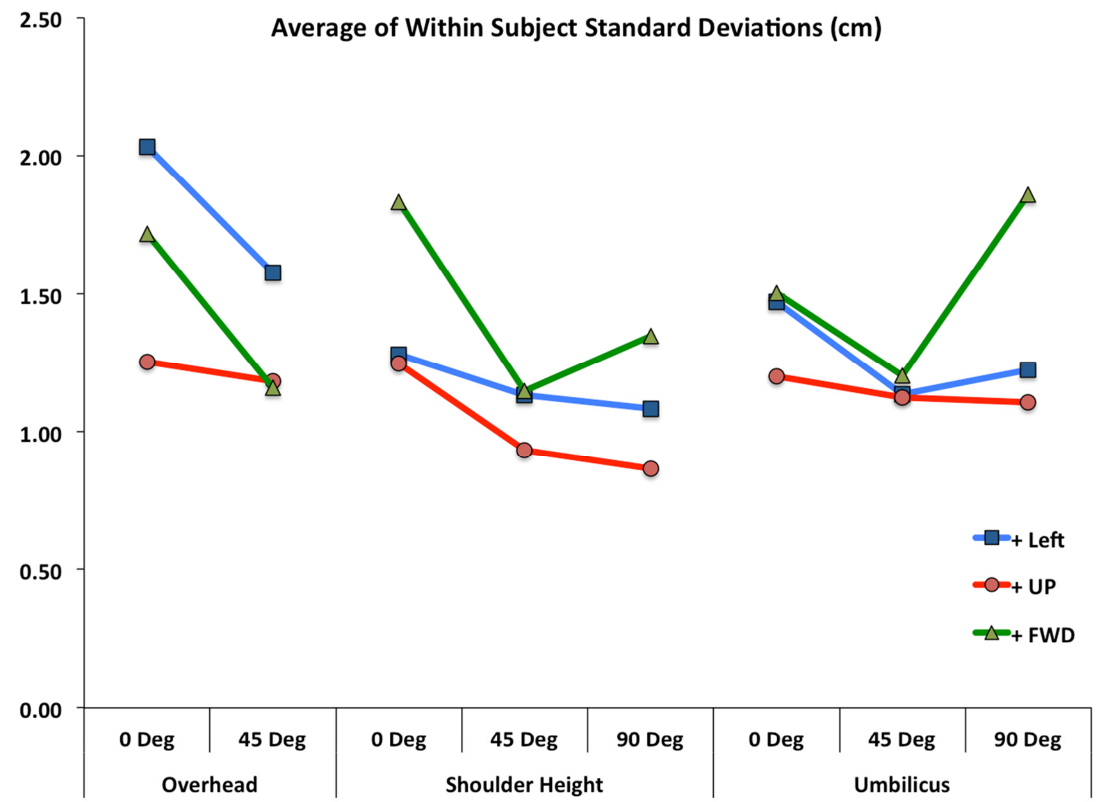


Figure 4.4: The average of the within-subject standard deviations for absolute shoulder location, collapsed across the 3-axes. For all the hand locations, the average location of the shoulder was found to be most variable in the forward direction (1.5 cm) and least variable for the up direction (1.1 cm).

4.3 –Regression Equations

4.3.1 – Comparison of Regression models with and without postural information

For the M_{ALL} model, the multiple regression analysis produced a model that explained 75.4% of the variance and had an RMS error of 9.1 N (Figure 4.5). This RMS error represents 13.5 % of the mean (67.4 N). The variables that were included in the stepwise model were the unit vectors in the left/right and up/down axes, the horizontal and vertical displacement of the hand to the shoulder, the elbow and shoulder vertical angles and the 3D moment arms to the shoulder and elbow (Table 4.2).

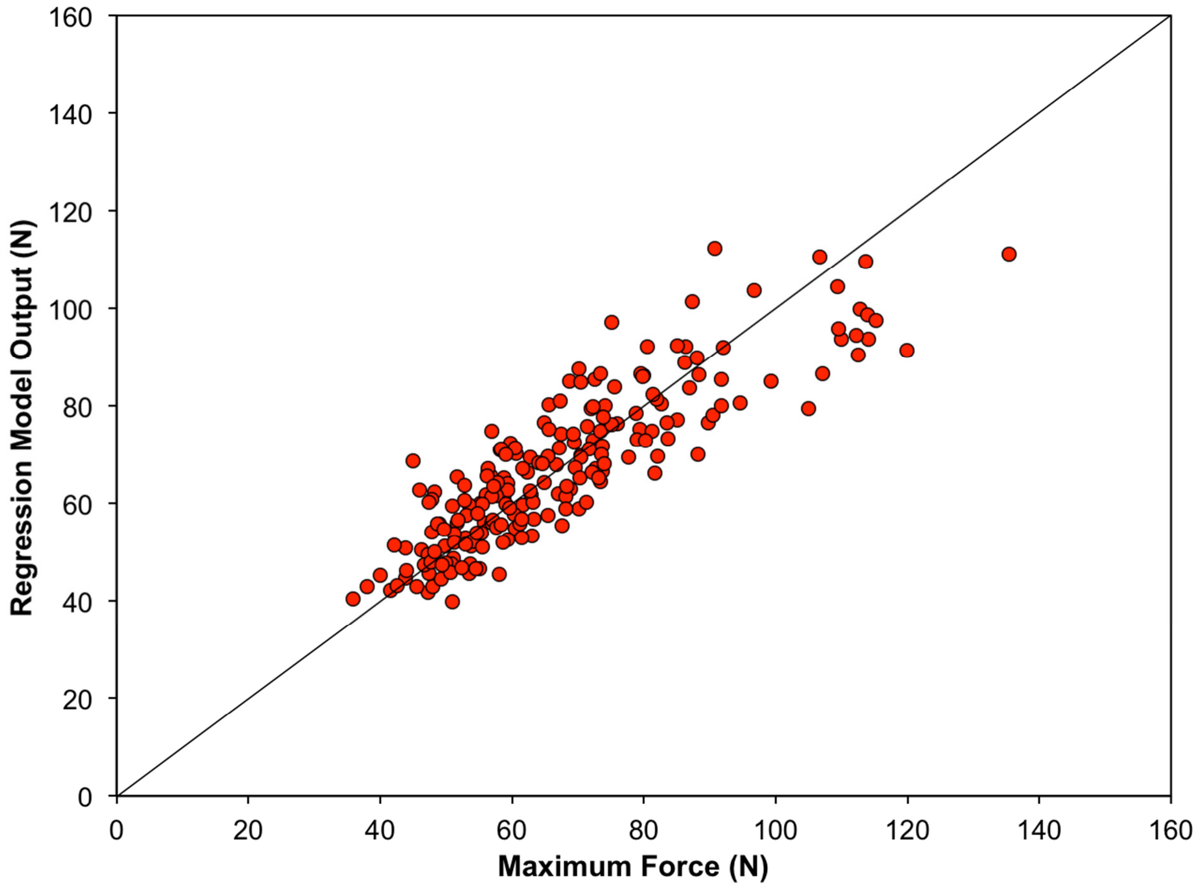


Figure 4.5: M_{ALL} regression results (n=208, 8 positions x 26 directions) with a line of perfect prediction. The R-square was 0.754 and the RMS error was 9.1 N.

Table 4.2: Regression summary for the predictive equation with all shoulder, hand and angle variables (M_{ALL}). n=17. Variables in grey were removed from the stepwise regression process.

Stepwise (F=2 to enter)
Strength vs. 11 Independents
Step: 12

Count	208
Num. Missing	0
|R|	0.86851978
R Squared	0.7543
Adjusted R Squared	0.74445029
RMS Residual	9.2818

ANOVA Table
Strength vs. 11 Independents

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	8	52640.41004	6580.051256	76.37731712	<.0001
Residual	199	17144.2288	86.15190352		
Total	207	69784.63885			

Variables In Model
Strength vs. 11 Independents
Step: 12

	Coefficient	Std. Error	Std. Coeff.	F-to-Remove
Intercept	131.713	12.296	131.713	114.751
Unit Vect. (Left/Right)	5.960	1.153	0.183	26.710
Unit Vect. (Up/Down)	-3.490	1.169	-0.110	8.922
Unit Vect. (Push/Pull)				
Hand Loc. (Left/Right)				
Hand Loc. (Up/Down)	125.388	24.800	1.542	25.563
Hand Loc. (Push/Pull)	24.084	6.897	0.180	12.192
Elbow Angle	0.193	0.107	0.123	3.268
Shld. Horiz. Angle				
Shld. Vert. Angle	-0.979	0.181	-1.734	29.156
Shoulder 3D MA	-133.011	6.725	-0.820	391.184
Elbow 3D MA	70.175	13.724	0.212	26.145

Variables Not In Model
Strength vs. 11 Independents
Step: 12

	Partial Cor.	F-to-Enter
Unit Vect. (Push/Pull)	-0.0904897	1.634685739
Hand Loc. (Left/Right)	0.06911693	0.950416049
Shld. Horiz. Angle	0.05742576	0.65510842

To test the importance of the added information provided by elbow and hand location, M_{NP} was developed by removing these inputs and only using the unit vectors, hand location and shoulder 3D moment arm as independent variables. M_{NP} demonstrated a lower predictive capacity by having an explained variance of only 67.3% and a higher RMS error of 10.5 N (Figure 4.6), or a -8.1% and +1.4 N difference, respectively (Figure 4.7). However, overall, the equation still predicts moderately well with the RMS error being 15.5% of the average maximum voluntary force (MVF) (67.4 N) and 9.3% of the MVF (110.5 N). Of the independent variables entered into the stepwise equation, only the 3D moment arm to the shoulder, the lateral displacement of the hand to the shoulder and the left/right and up/down unit vectors were included in the model (Table 4.3).

Table 4.3: Regression summary for the multi-dimensional equation with only the unit vector, hand location and shoulder 3D moment arm variables. . Variables in grey were removed from the stepwise regression process.

Stepwise (F=2 to enter)
Strength vs. 7 Independents
Step: 4

Count	208
Num. Missing	0
|R|	0.82041
R Squared	0.67307
Adjusted R Squared	0.66663
RMS Residual	10.60127

ANOVA Table
Strength vs. 7 Independents

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	4	46970.09087	11742.52272	104.482987	<.0001
Residual	203	22814.54798	112.3869359		
Total	207	69784.63885			

Variables In Model
Strength vs. 7 Independents
Step: 4

	Coefficient	Std. Error	Std. Coeff.	F-to-Remove
Intercept	115.1778	2.5595	115.1778	2025.0408
Unit Vect. (Left/Right)	7.0722	1.3056	0.2176	29.3427
Unit Vect. (Up/Down)	-4.3948	1.2789	-0.1380	11.8088
Unit Vect. (Push/Pull)				
Hand Loc. (Left/Right)	28.4540	4.3500	0.2642	42.7871
Hand Loc. (Up/Down)				
Hand Loc. (Push/Pull)				
Shoulder 3D MA	-115.4448	6.5510	-0.7116	310.5476

Variables Not In Model
Strength vs. 7 Independents
Step: 4

	Partial Cor.	F-to-Enter
Unit Vect. (Push/Pull)	-0.0828076	1.394697831
Hand Loc. (Up/Down)	-0.071479	1.037367805
Hand Loc. (Push/Pull)	0.06966087	0.985012407

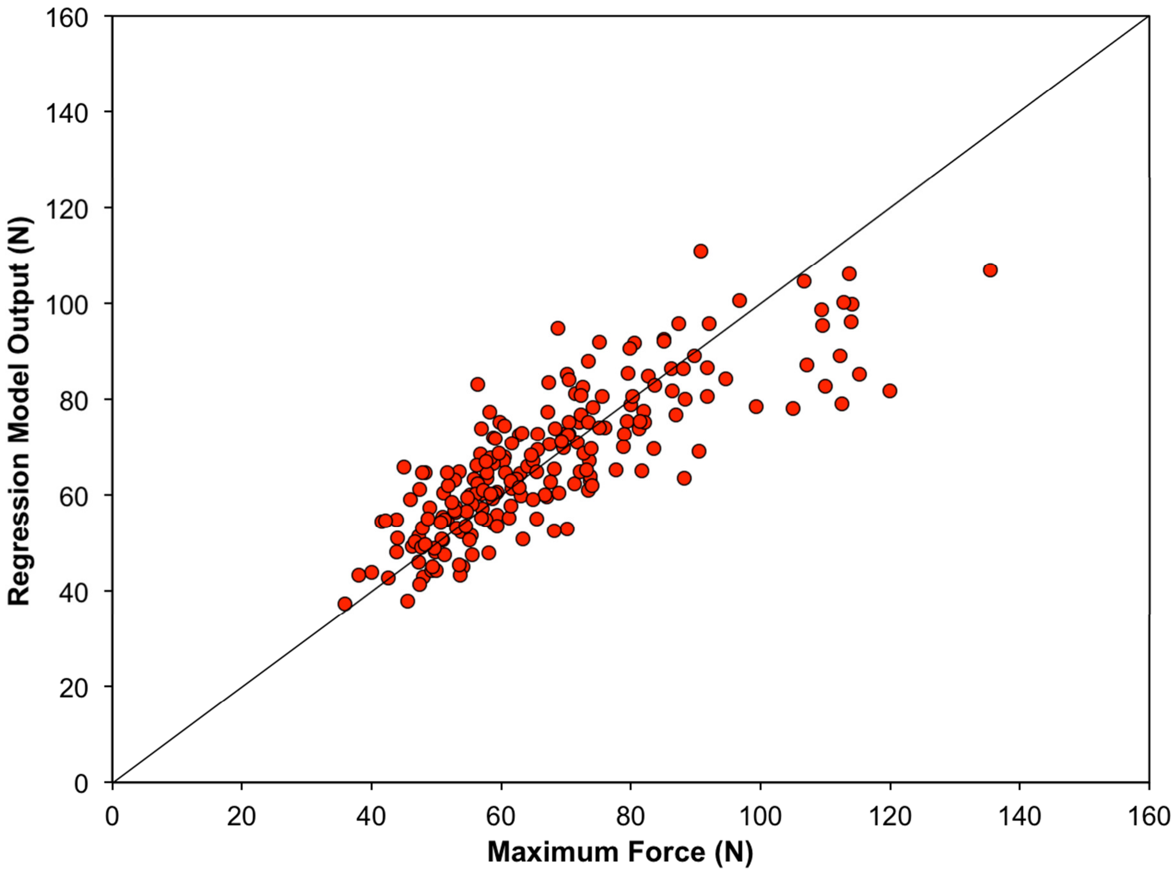


Figure 4.6: M_{NP} regression results (n=208, 8 positions x 26 directions) with a line of perfect prediction. The equation was developed with only the unit vector, hand location and shoulder 3D moment arm variables forced in. The R-square was found to be 0.685 and the RMS error was 10.3 N.

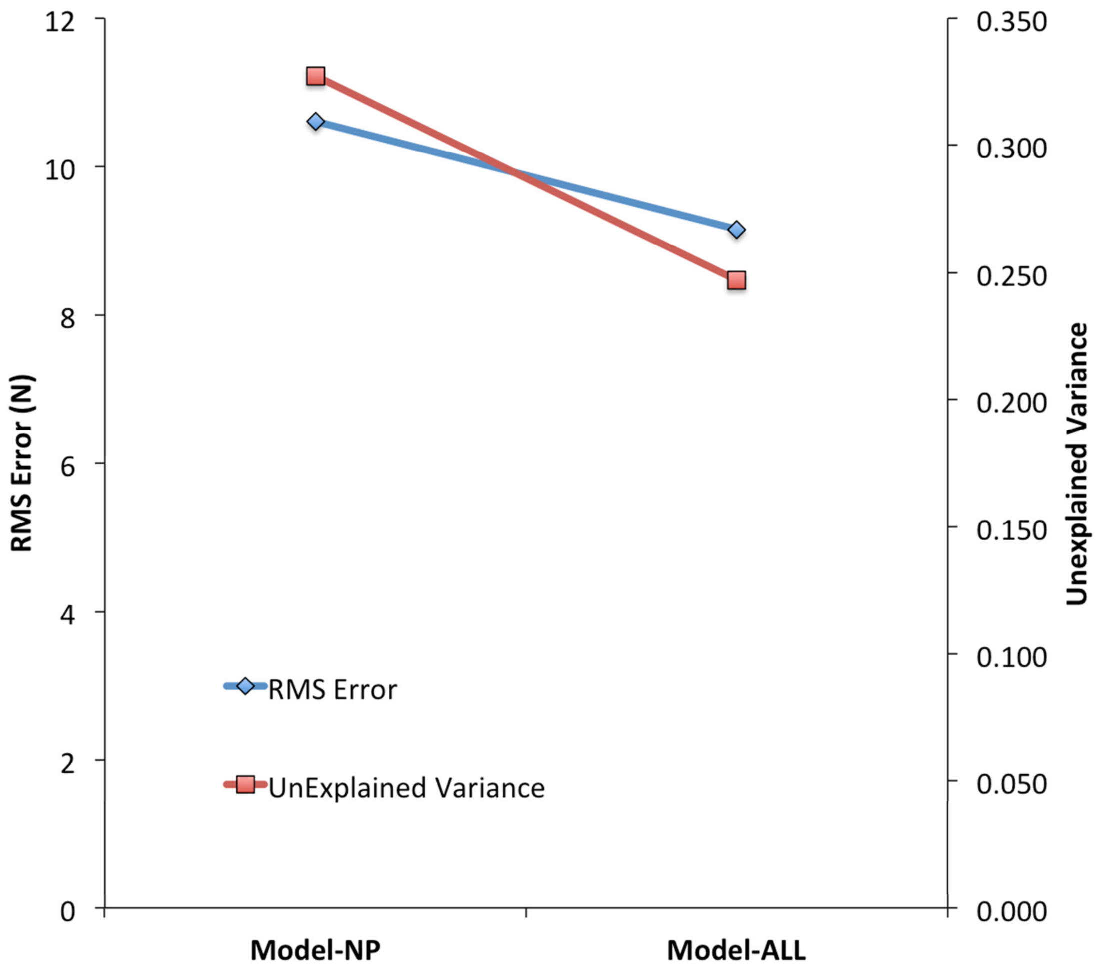


Figure 4.7: A comparison of RMS error (N) and unexplained variance (1.0 – r^2) between M_{ALL} and M_{NP}. The predictive performance of $M_{ALL}$was improved with the kinematic variables such as elbow and shoulder angles, and elbow 3D moment arms being included as independent variables in the predictive regression equations.

4.3.3 – Test of Interpolative continuity of regression equations

M_{NP}, with only the hand location and shoulder moment arms as inputs, was used to graphically test how well the equations interpolate within the reach envelope at H, V and L's not collected in the study. It was found that at every hand location height, the interpolated predicted strengths followed along the expected curve (Figure 4.8). Table 4.4 shows how the regression equation predicts these uncollected values and Figure 4.8 provides a visual representation of the continuitity between strength means for each measured and unmeasured hand location.

Table 4.4: Predicted average strength results of the interpolated hand locations compared to the predicted and actual strengths of known hand locations (dark rows).

		Strength	
	Angle	**Prediction (N)**	**Actual (N)**
Shoulder	0.00	72.8	77.7
	11.25	71.9	
	25.00	70.7	
	33.75	69.2	
	45.00	67.4	66.9
	56.25	65.4	
	67.50	63.1	
	78.75	60.6	
	90.00	57.3	56.4
Umbilicus	0.00	75.3	77.7
	11.25	74.3	
	25.00	73.2	
	33.75	72.1	
	45.00	70.7	68.1
	56.25	69.3	
	67.50	67.8	
	78.75	66.0	
	90.00	64.2	63.1
Overhead	0.00	69.0	68.2
	11.25	67.6	
	25.00	66.2	
	33.75	64.8	
	45.00	63.4	62.1
	56.25	62.1	
	67.50	60.8	
	78.75	59.4	
	90.00	58.2	

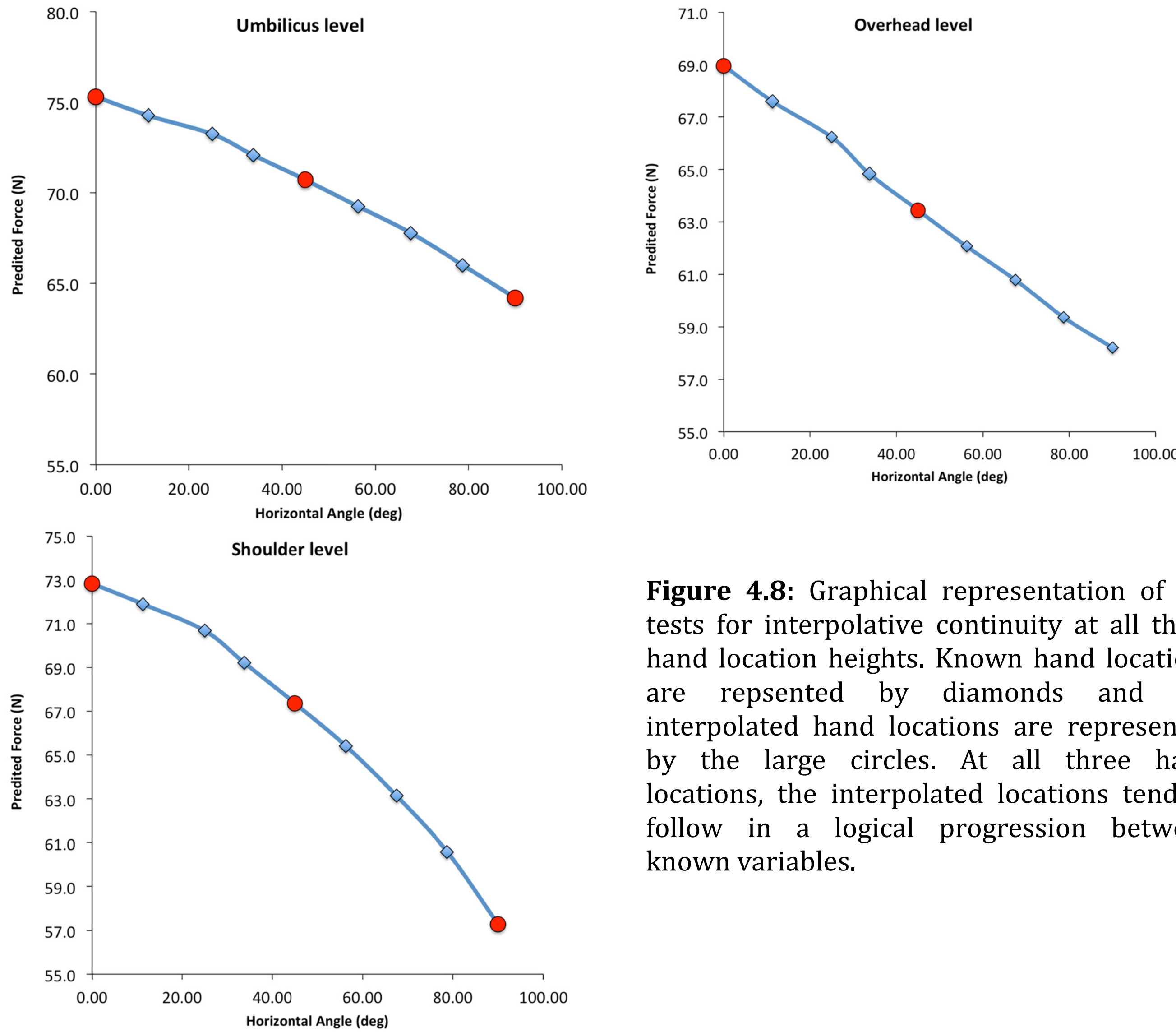


Figure 4.8: Graphical representation of the tests for interpolative continuity at all three hand location heights. Known hand locations are repsented by diamonds and the interpolated hand locations are represented by the large circles. At all three hand locations, the interpolated locations tend to follow in a logical progression between known variables.

4.4 – 3DSSPP Validation

When combining the 36-hand locations from Potvin et al. (2010) with the 8-hand locations from this thesis, the overall correlation between 3DSSPP's 50th percentile capable values (ie. mean strength) and the actual empirical strength data was low (r=0.305). This represents an unexplained variance of 90.7% and an RMS error of 39 N, or approximately 4 kg (Figure 4.9). Overall, this RMS error is 45% of the measured average values.

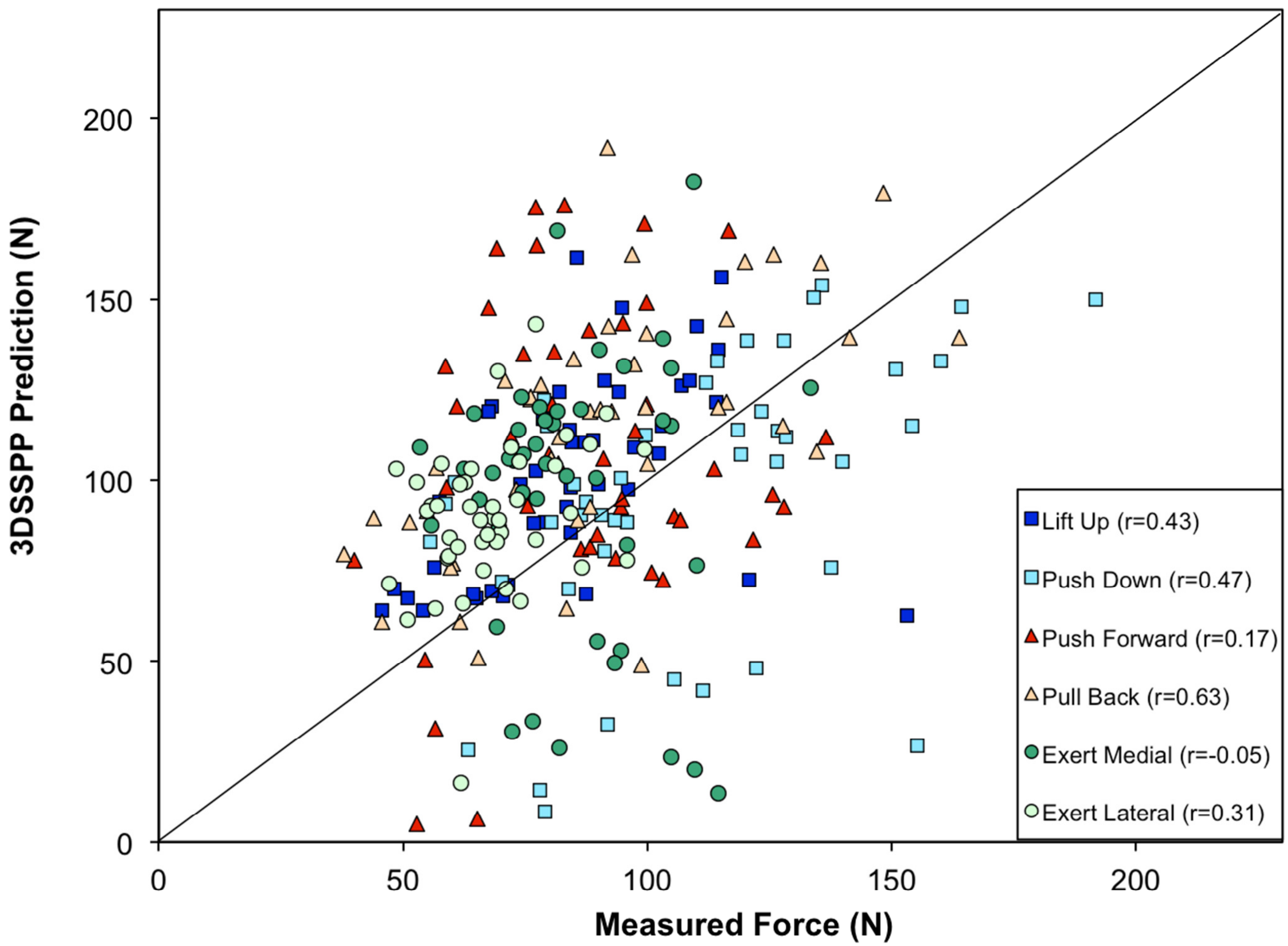


Figure 4.9:. Correlation (r=0.305) of the 3DSSPP 50% capable values to the pooled measured 1D forces from Potvin et al. (2010) and this thesis (n=264 comparisons).

The most highly correlated 1D direction was the “pull” direction (r=0.63), however the lowest RMS error was seen in the lateral direction (29 N). The RMS error and unexplained variance ($1.0 - r^2$) tended to follow the same relative magnitude between exertion directions and heights (Figure 4.10). The 3DSSPP software performed the worst in the medial direction with a negative correlation of -0.05 (RMS error of 44 N)(Table 4.5).

In terms of exertion height, it appears that 3DSSPP predicts most accurately at stature height (r=0.67, RMS error of 23 N), however there were only 12 total comparisons at this height, which is the lowest sample size for any given exertion height. The exertion height, at which 3DSSPP predicted most poorly, was the overhead location, with an RMS error of 48 N (55% of average MVF).

When examining the average error, only one of the exertion direction or hand location metrics was under-predicted (pull down)(Figure 4.11). This shows that 3DSSPP tended to over-predict maximal arm strength by an average of 11.7 N. Though the average errors, within direction or height, were almost exclusively over-predictions, about 50% of the greatest peak errors occurred when 3DSSPP under-predicted the empirical strengths (Figure 4.12). A full table of the 3DSSPP H, V and L inputs, as well as the 50^{th} percentile force and limiting joints can be found in Appendix F.

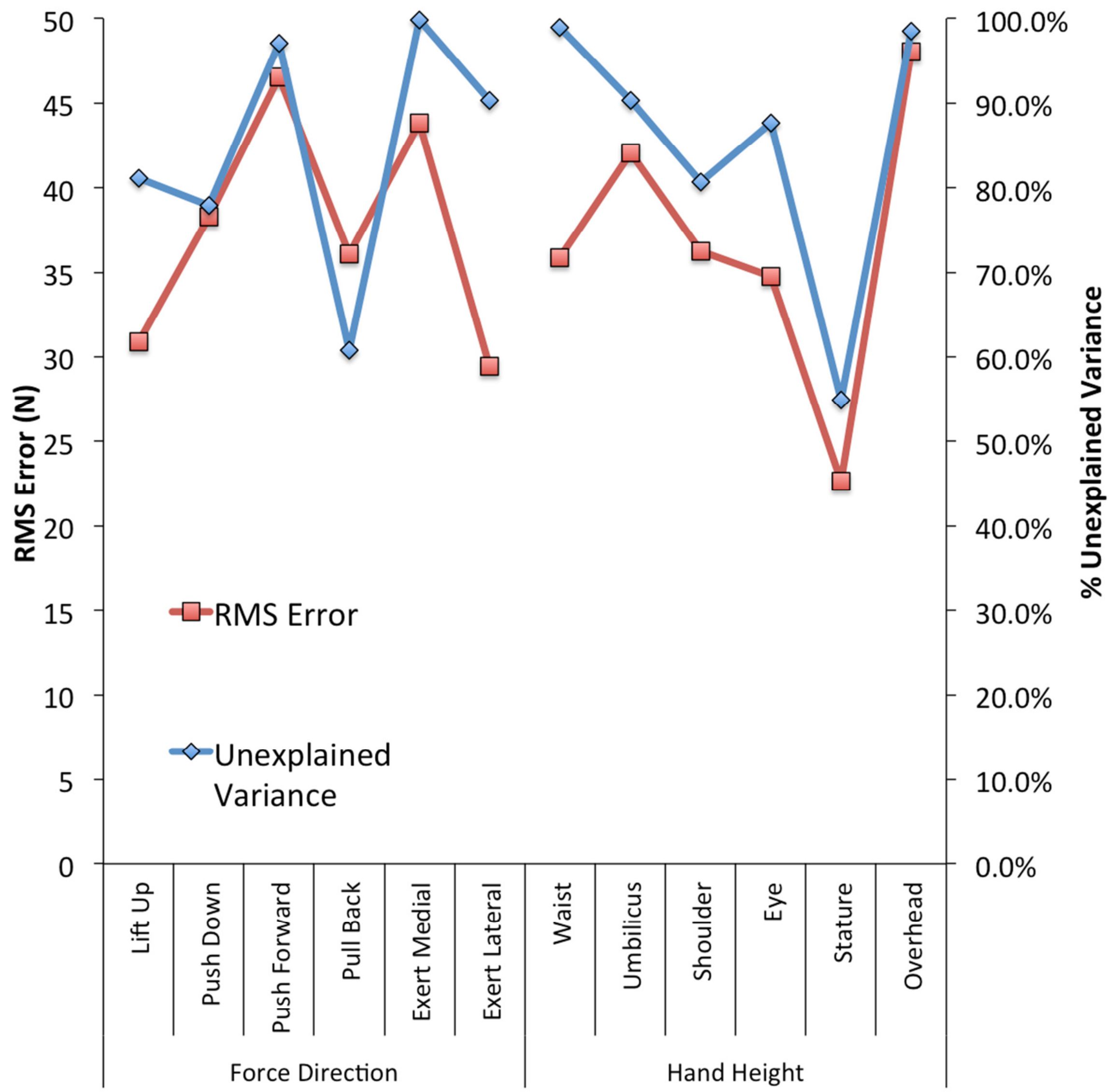


Figure 4.10: Shows the relative trend between RMS error and unexplained variance between exertion directions and heights for the comparison between the empirical data and 3DSSPP.

Table 4.5: Validation statistics between the 3DSSPP 50th percentile values and the pooled measured 1D forces from Potvin et al. (2010) and this thesis (n=264).

		3DSSPP Comparison Results				
			Correlation		RMS error	
	Condition	n	r	Unexplained variance	N	lbs
Force Direction	Lift Up	44	0.43	81.1%	30.9	6.9
	Push Down	44	0.47	78.0%	38.3	8.6
	Push Forward	44	0.17	97.1%	46.6	10.4
	Pull Back	44	0.63	60.7%	36.1	8.1
	Exert Medial	44	-0.05	99.8%	43.8	9.8
	Exert Lateral	44	0.31	90.3%	29.4	6.6
Hand Height	Waist	36	0.10	99.0%	35.9	8.0
	Umbilicus	60	0.31	90.2%	42.1	9.4
	Shoulder	78	0.44	80.7%	36.3	8.1
	Eye	54	0.35	87.6%	34.8	7.8
	Stature	12	0.67	54.9%	22.6	5.1
	Overhead	24	0.12	98.5%	48.0	10.8
	All	**264**	**0.31**	**90.7%**	**39.0**	**8.7**

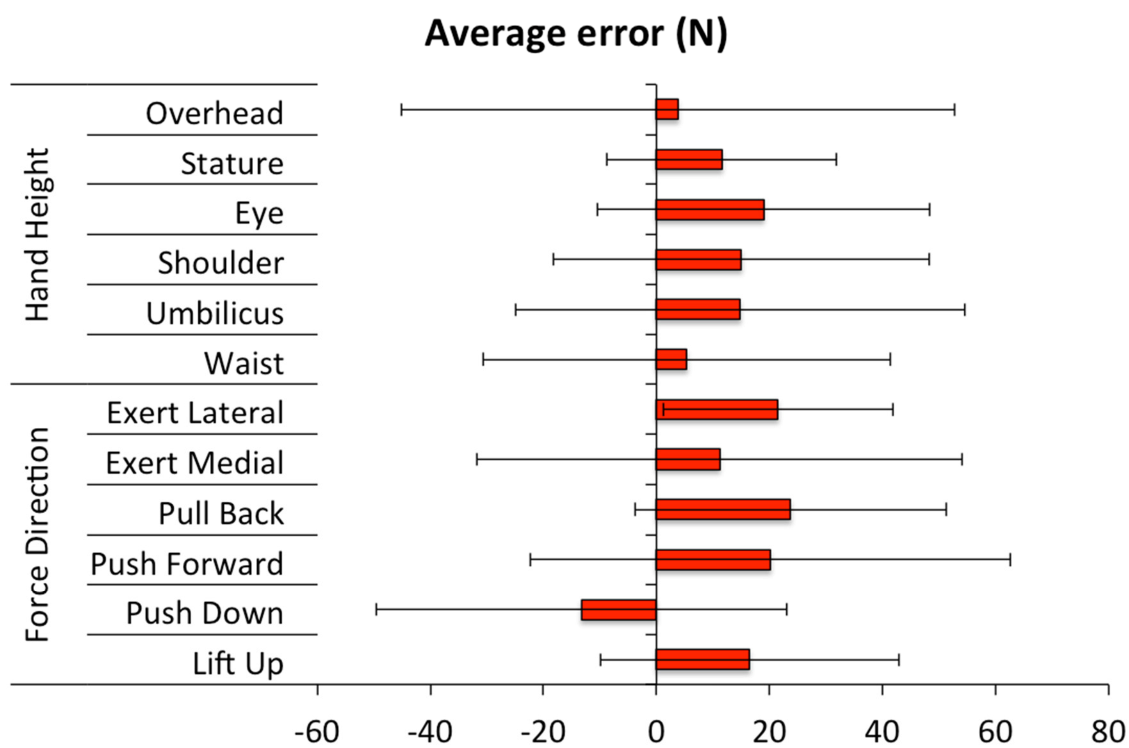


Figure 4.11: Average Error (N) for each exertion height and direction. Positive errors indicate that 3DSSPP over-predicted the actual force.

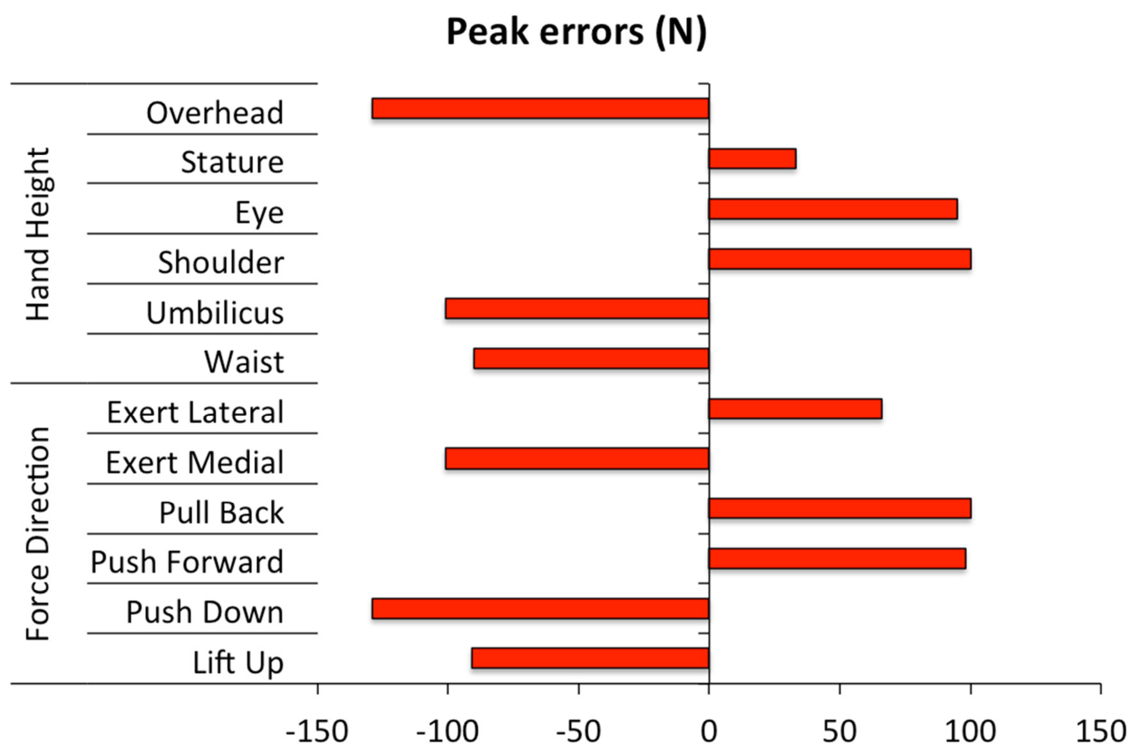


Figure 4.12: Maximal average (peak) errors that occurred at each exertion direction and height between empirical data and 3DSSPP.

Table 4.6: The most common limiting joints (bolded) for each exertion direction in the 3DSSPP comparison to empirical data (n=44 comparisons each).

Joint	Up	Down	Push	Pull	Medial	Lateral
Elbow	7%	23%	25%	2%	0%	**36%**
Shoulder	39%	**70%**	**64%**	**61%**	**75%**	27%
Wrist	**55%**	7%	11%	36%	25%	**36%**

CHAPTER 5 - DISCUSSION

The main purpose of this thesis was to measure arm strengths in the 1D, 2D and 3D exertion directions and to determine whether the inclusion of more specific information, regarding arm location and posture, would improve the predictions of arm strength. Of the 8 hand locations tested in this thesis, the strongest tended to be at the Shoulder and Umbilicus heights at the 0° hand locations, followed by the Overhead at 0° hand location. It was found that the strongest exertion directions at each hand location tended to be those that were in-line with the arm, suggesting that the 3D moment arms of the force vectors from hand to shoulder, and hand to elbow, were important variables in the determination of arm strength. It was also observed that the highest CV's within the 208 conditions tended to be in the 1D directions, and the lowest CV's tended to be in the 3D directions.

In the comparison of regression models (n=17) with (M_{ALL}) and without (M_{NP}) postural information, the M_{ALL} model (r^2 = 0.754, RMSE = 9.1 N) performed better than the M_{NP} model (r^2 = 0.673, RMSE = 10.5 N) by explaining 8.1% more variance and having a reduced RMS error by 1.4 N, highlighting the importance of the additional postural variables.

In the 3DSSPP comparison, the overall correlation between 3DSSPP's 50th percentile capable values and empirical strength data was found to be low (r = 0.305). With an RMS error of 39 N, this is approximately 50% of the maximal acceptable force level at Ford Motor Company for one armed exertions (~76 N). It was also found that 3DSSPP tended to over-predict maximal arm strength by an average of 11.7 N, in all direction and height conditions except for the push down exertion. This is potentially a concern for ergonomists, that would generally prefer a conservative approach to strength estimation rather than over-estimating the strength of the population.

5.1 Arm Strength

In terms of the measured strength data in this study, some interesting trends were observed when comparing the strengths of the different exertion directions at various hand locations. As expected, the highest mean strength values tended to occur when the largest muscle groups, such as the pectoralis major and latissimus dorsi, would have been dominant contributors to the force at the hand. For example, the strongest overall hand locations observed in this study were at the Shoulder and Umbilicus heights with the hand directly in front of the shoulder (0°). With the hand being located directly in front of the right shoulder, the pectoralis major and latissimus dorsi muscles could make a substantial contribution to the push and pull forces, respectively. This effect was also observed at the 45° and 90° degree shoulder angles. As can be seen in the polar plots representing strengths in the different exertion directions (see Figure 4.2), the highest forces for each hand location tended to occur when the direction of force was in line with the arm or, effectively, when the resultant moment arms of the force vector from the shoulder and elbow to the hand were small for a given exertion direction. The strongest directions were push and pull at 0 degrees; pull/medial and push/lateral at 45 degrees and medial and lateral at 90 degrees. Overall, across all 208 conditions, the highest overall strength (135.4 ± 55.0 N) was observed for pulling when the hand was at shoulder heigh and 0°. As discussed previously, this would have been expected due to the biomechanical advantage of the lattisimus dorsi muscle group at this hand location and exertion direction. The lowest overall strength (35.9 ± 8.7 N) was observed when the hand was at shoulder height at 90° in the up/pull direction. With the arm fully abducted to 90°, as it is in this hand location, the 3D moment arm of the force vector in the up/pull direction to the shoulder and elbow are both very large (0.52 m), and therefore the contribution of the larger muscle groups are limited in this exertion direction. It is intereting to note that the highest and lowest forces resulted in very similar moments of 18.6 and 18.4 Nm, respectively. Both were substantially lower than the highest average moment observed to be 35.8 Nm for Up/Push/Right direction at the Umbilicus/0 degrees. hand location

These strength trends, as illustrated in figure 4.2, provide a telling story about the relationship between moment arms and maximal strength. In order to examine whether this postulation had mathematical merit in this thesis, the strengths for each hand location and exertion direction were correlated with their associated resultant 3D shoulder and elbow external moment arms. It was found that both comparisons exhibited a negative correlation as expected, however the shoulder 3D moment arm had a much stronger correlation with strength of $r = -0.74$

compared to that of the elbow 3D moment arm (r = -0.18) (Figure 5.1). This shows that approximately 54% of the explained variance seen in the M_{ALL} and M_{NP}, models was accounted for by the shoulder moment arm alone. This is a very interesting finding, given how complex the shoulder muscles are, because the direction of the force does not seem to be nearly as important as the moment arms in the prediction of force.

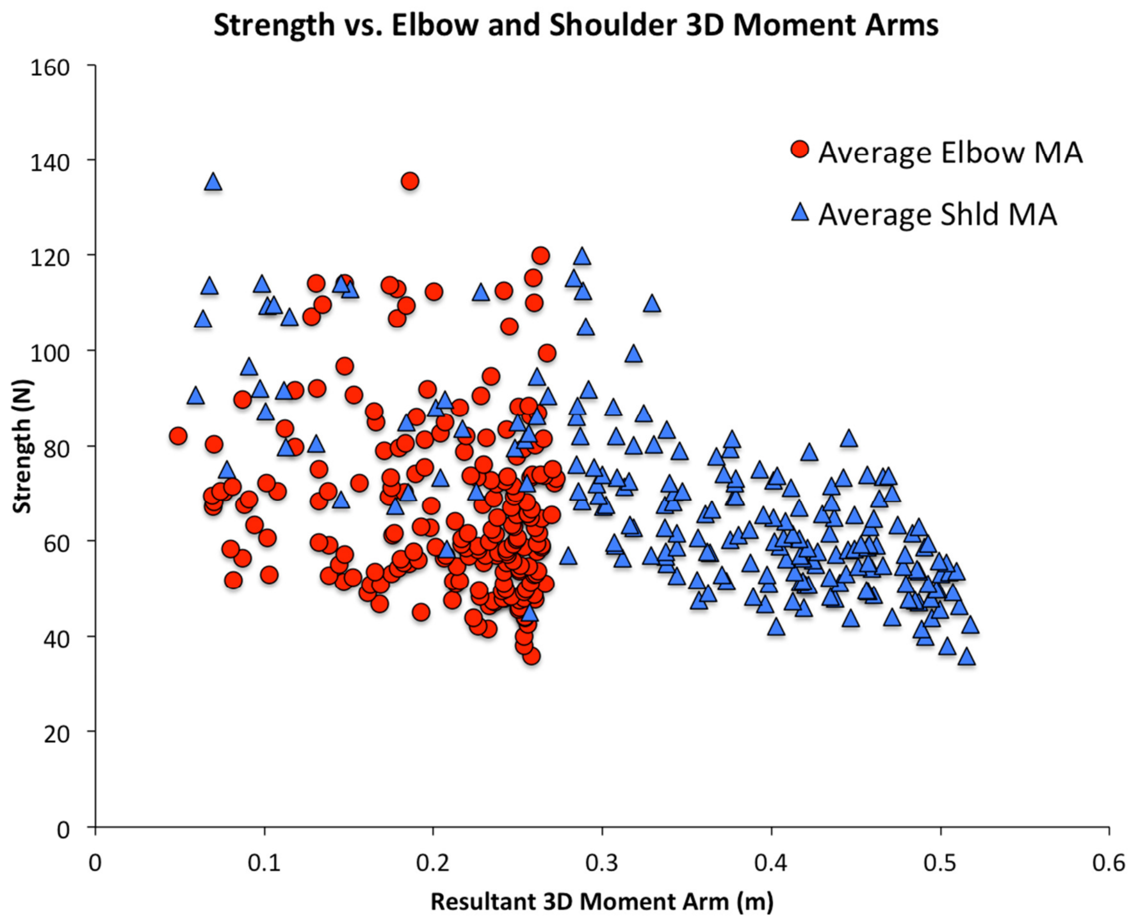


Figure 5.1: Correlations when comparing the 1D, 2D and 3D strengths to both the shoulder (r = -0.74) and elbow (r = -0.18) resultant moment arms of the force vector.

When comparing the maximal strength values from this thesis to previous studies, the strengths from this study tends to be slightly lower in most cases. As previously discussed in section 2.2.5.1, even small differences in whole body and arm posture can affect arm strength measures, so only hand locations and whole body postures that are similar to this thesis will be discussed. The previous studies that were most similar to this thesis, in terms of methodology and hand locations, were those in Potvin et al. (2010). In the hand locations that were determined to be the most similar to the current study, the strengths from this thesis tended to be about 82% of those in Potvin et al. (2010) (Table 5.1). The largest differences were seen in the Overhead hand locations, with the average ratios of Potvin et al. (2010) strengths to the strengths tested in this thesis being 74%, at the Overhead 0° and 45° hand locations. This was somewhat expected as the overhead location, as defined in Potvin et al. (2010), was at a much higher vertical distance (V=0.473 m compared to V=0.254 m for current study at Overhead 0°), and smaller horizontal distance relative to the shoulder (H=0.1 m compared to H=0.432 for Overhead 0°). In other words, the subjects' arms in Potvin et al. (2010) were more severely angled overhead compared to the current study where the overhead position had more of a forward component. This explains why the up and down strengths were much higher in the Potvin et al. (2010), but also why the push and pull forces were larger in the current study. In the remaining hand locations that matched more closely between studies, the Potvin et al. (2010) to current study force ratios were not as severe, ranging from 83 to 90%

Table 5.1: Force ratios between the current study and the most similar hand locations from Potvin et al. (2010). Hand locations in Potvin et al. (2010) are presented as Exertion height/angle/% of maximum reach. Ratios are presented as the current study divided by Potvin et al. (2010). All the hand locations and 1D exertion directions means tended to be higher in Potvin et al. (2010).

Hand Locations		**Force Ratios [Current/Potvin et al. (2010)]**						
Potvin et al. (2010)	Current Thesis	Up	Down	Push	Pull	Left	Right	Mean
Overhead/0	Overhd @ 0	0.40	0.51	1.38	1.38	0.80	0.76	87%
Overhead/45	Overhd @ 45	0.66	0.54	0.73	0.64	0.66	0.71	66%
Shld/0/80%	Shld @ 0	0.87	0.79	0.83	0.91	0.97	0.96	89%
Shld/45/80%	Shld @ 45	0.84	0.62	0.77	0.82	0.83	0.92	80%
Shld/90/80%	Shld @ 90	0.79	0.70	0.76	0.74	0.82	0.92	79%
Belly/0/80%	Umbil @ 0	0.77	0.86	0.85	0.95	0.87	0.84	86%
Belly/45/80%	Umbil @ 45	0.72	0.84	0.90	0.83	0.77	0.86	82%
Belly/90/80%	Umbil @ 90	0.86	0.81	0.96	0.80	0.92	1.06	90%
	Mean Ratio	74%	71%	90%	88%	83%	88%	**82%**

Chow and Dickerson (2009) provided the next closest methodology to the current thesis in order to evaluate maximal arm forces. The most similar hand locations from Chow and Dickerson (2009) would be what they termed their 0° angle relative to the horizontal plane through the shoulder (analogous to Shoulder at 0° in the current study), and their 30° angle relative to the horizontal, which would be at a lower relative vertical height compared to the Overhead at 0° condition in the current study. Chow and Dickerson (2009) collected maximal force data in three exertion directions: down, push and left (medial). In comparing the Shoulder at 0° hand location, the most similar exertion direction was found to be exerting medially (difference of 8 N). The largest difference was seen in the down direction, where Chow and Dickerson (2009) observed a downward strength of 158 ± 59 N as compared to 79 ± 33 N for the current study, representing a difference of 79 N (Table 5.2). At comparable overhead locations, the largest difference was again observed in the down direction by nearly 111 N. The most similar strength between the studies was again seen in the medial exertion direction. Perhaps the major consideration leading to some of these large differences in strength, particularly in the down direction, is that Chow and Dickerson (2009) had their subjects keep their left hand at their side rather than using it to provide a counter-torque as in the current study. This would explain why the push forces were greater in the current study, as subjects had the ability to produce a counter-moment with their left hand to balance the larger pushing force with the right hand, therefore allowing the subjects to maintain a neutral posture. The other difference between the studies that could have contributed to such a large discrepancy in the down direction is the orientation of the handle. In Chow and Dickerson (2009), the handlebar was oriented horizontally during the down exertion directions rather than vertically. This may have allowed subjects to effectively hang off the handlebar without being as limited by wrist ulnar deviation as they may have been with the vertical handlebar in the current study. This trend was also observed in Potvin et al. (2010), where it was shown that a horizontal handlebar orientation resulted in a 16% higher average strength at the Head at 0° hand location, compared to a vertical handlebar orientation. One last, but very important, discrepency between the two protocols is that Chow and Dickerson (2009) set their reach distance to be 50% of maximal reach, compared to 80% in this study. By having the hand exerting forces closer to the body with a smaller external moment arm, the strengths observed in Chow and Dickerson (2009) would be expected to be higher, especially in the down and left directions. This moment arm difference would not be expected to be as pronounced for the push direction, where the difference in arm reach would not have as large of an effect on the in-line pushing force, as the resultant moment arms of the force vectors are small in both studies at a 0° shoulder angle.

Table 5.2: Comparison of strength results from similar hand locations and exertion directions in Chow and Dickerson (2009) and the current study. The shoulder at 0° condition was considered to be analogous to the standing and 0° angle condition from Chow and Dickerson (2009) and the Overhead at 0° was considered to be analogous to the standing, 30° angle condition from the same study. Means, standard deviations and the difference in means are presented.

		Strength (N)		
Hand Location	**Direction**	**Chow & Dickerson (2009)**	**Current Study**	**Difference**
Shoulder at 0 deg	Down	158 ± 59	79 ± 33	79
	Push	61 ± 14	114 ± 39	-53
	Left	64 ± 11	72 ± 26	-8
Overhead at 0 deg	Down	190 ± 59	79 ± 33	111
	Push	52 ± 15	90 ± 35	-38
	Left	66 ± 10	56 ± 16	10

Garg et al. (2005) tested isometric strength at six arm postures defined by shoulder vertical angle and elbow angle. Maximal strength was defined as the maximal weight that could be held by the subject for 4 seconds at the given hand location with no signs of shaking or significant deviations in posture. At the 0-90 arm posture, similar to the Umbilicus at 0° arm posture in the current study, the lifting strength observed in Garg et al. (2005) was 88.3 ± 16.5 N. This strength was similar to the observed strength for the up exertion direction in the current study at the Umbilicus at 0° location, which was determined to be 82.1 ± 43.8 N, a 6.2 N difference in mean strength. When comparing the moments at this same hand location, Garg et al. (2005) observed a shoulder moment of 29.2 N.m as compared to 27.3 N.m in the current study.

There are several other studies that have collected arm strength data in a number of manners, however not all of them are easily comparable to this data set. Haslegrave et al. (1997) and Roman-Liu and Tokarski (2005) collected arm strength data as a function of whole body, and upper limb posture, respectively, however both of these studies collected strengths on male subjects only. The data from Stobbe (1982) is difficult to compare to the current study because of the seated positions of the subjects, as well as the differing point of force application. In Stobbe (1982), the forces were measured at the distal end of the humerus, therefore making the arm exertions more representative of shoulder strength rather than arm strength.

Coefficient of variation (CV's) were calculated based on the means and standard deviations of the 208 conditions in the current study. The mean CV, pooled across the 208 individual CVs, was found to be 33.4%, which is similar to the 30.6% found in Potvin et al. (2010). CV's are important in strength research as they can be used to convert mean strength data to Z-scores, which in turn can be used to determine what forces can accommodate a certain percentage of the population. In ergonomics, tolerance limit values (TLV's) are often set based on the strength requirement that 75% of females, or a Z-score of -0.67, are capable of producing a certain force. In this current study, the CV's ranged from 16.4% to 55.9%, with the lowest CV being the up/push/left exertion direction at Overhead at 45°, and the highest being in the right exertion direction at the Shoulder at 90° hand location. It was found that approximately 80.3% of the 208 conditions had CV's between 20% and 40%.

Another trend noticed when examining the CV's in the study was that the CV's tended to decrease from the 1D exertions directions to the 3D directions. The average CV of the 1D, 2D and 3D exertion directions were 39.4%, 32.3% and 30.8%, respectively. This implies that as the complexity of the task increased in terms of adding more exertion directions, the subjects were not as variable as a percentage of the mean as they were when only exerting in one direction.

5.2 Regression Equations to Predict Arm Strength

In the development of regression equations, improvements in predictive accuracy were seen when the elbow location and elbow and shouler postural variables were included in the M_{ALL} model, as compared to the M_{NP} model. Though both equations were in the moderate range of prediction accuracy, according to Vincent (2005), there was a substantial improvement in explained variance (8.1%) and RMS error (1.4N) in the M_{ALL} model. These results also agree with Hypothesis 1; that adding the extra postural and elbow terms would increase the predictive accuracy of the regression models. Though the model did not perform with good accruacy, or an R-squared of 0.81 or over as postulated in Hypothesis 1, an explained variance of 75.4% is considered to be at the high end of a moderate prediction according to Vincent (2005) and is an improvement from the multidimensional model developed by Potvin et al. (2010), that exhibited an explained variance of 0.626 and an RMS error of 17.1N. Furthermore, it was observed that, at the higher forces of over 100N, the models tended to under-predict the actual force. If these large errors in the high force range were not present, there would be a lower RMS error between the regression model and actual forces. Some of the largest errors were observed at a force level above 120 N, which converts to about 12 kg or 27 lbs, well above recommended force limits typically used in industry for one-armed tasks. When 120N forces and above were removed from the comparison between the development model predictions and the independent test group, the RMS error decreased from 13.7 N to 11.2 N. In the inspection for a continuous trend between predicted strength values at interpolated hand locations, and those that were measured in this thesis, the results failed to reject Hypothesis 2; that a continuous trend will be seen at all three exertion heights when the arm angle is changed from 0° to 90° and inputted into M_{NP} (see Figure 4.11).

In the M_{ALL} model, the inputs that explained the most variance were: 1) shoulder 3D external moment arm, 2) vertical hand location and 3) the elbow 3D moment arm. The role of the shoulder 3D moment arm also explained the most variance in the M_{NP} equation. These 3D moment arms likely explain much of the vairance because, for a given maximum moment, a larger moment arm will result in a lower force. It was surprising that the elbow flexion, horizontal shoulder and vertical shoulder angles did not get represented very strongly in the M_{ALL} equation. A possible explanation for this unforeseen finding was that the variance explained by the angle terms could have already been explained by the 3D moment arm terms, as they were partly developed using radius vectors terms from the shoulder and elbow. It is also important to consider what variables may have been missing and could have reduced the overall unexplained variance in the model if they had been included. It may be possible to include more sophisticed kinematic measures in future studies, such as shoulder rotation, as well as other kinetic measures such as shoulder and elbow moment in an attempt to explain more variance.

It is interesting to note that the multidirectional equations that were developed in this thesis performed better than those developed previously by Potvin et al. (2010). In Potvin et al. (2010), a process of determining dot product estimates of the maximal 2D and 3D forces, based on the 1D maxes in the respective directions, was undertaken and used as an input to the regression equation. One limitation of this dot product estimation of maximal forces was that the estimates were insensitive to changes in moment arms when the exertion directions were combined, and thus tended to be fairly inaccurate. In this thesis, the dot product estimates were not used to develop the equation, in favour of maintaining a simpler paradigm, in which only precisely measured variables (with no significant mathematical estimations) were included in the equation. It is also likely that the predictive equations developed in this thesis were based on more precise kinematic measurements, and therefore did not propagate as many errors when determining more complex variables, such as the 3D external moment arms.

The overall implications and lessons learned from the regression analyses conducted was that having an accurate representation of hand, elbow and shoulder location made a valuable contribution to explaining the variance in average female arm strength. One drawback of this method is that it is not always easy to obtain accurate kinematic information in the field. One of the strengths of the 1D equations developed in previous literature (Potvin et al., 2010; Freeman et al., 2006) is that by only including inputs of H, V and L at the hand, this made for fairly accurate and relatively simple measurements by ergonomists in the field. It would be very difficult to maintain this level of accuracy and simplicity when variables such as arm angle and elbow H, V and L also have to be measured, therefore making this approach much more suitable within digital human models.

5.3 - 3DSSPP Comparison

The comparison with the University of Michigan's 3DSSPP ergonomic tool strength outputs resulted in some serious concerns over its ability to predict 50-percent capable strengths in females for 1D exertions. In particular, it was found that the average RMS error was 39 N, which is an error that is 51% of the maximal acceptable force level at Ford Motor Company for one-armed exertions (76N lbs). When looking at Figure 4.12 and the widespread scatter of data, as well as the average error (Figure 4.15), it appears that 3DSSPP tended to over-predict the actual measured strengths from this thesis and Potvin et al. (2010). This result disagrees with Hypothesis 3; that the strength predictions provided by 3DSSPP will correlate strongly (r=0.8) with the empirical strength database, and that the average errors will be evenly distributed between being over- and under-predictions. Every hand height and force direction condition, except for Push Down, had a positive average error, meaning an over-prediction on the part of 3DSSPP. A possible explanation for why the Push Down condition was the only one under predicting could be due to the methodological differences between the current strength collections and those used in 3DSSPP. Stobbe (1982) collected all of its strength data with subjects in a seated and restrained position, while Potvin et al. (2010) and the current study that had subjects standing, such that they were able to apply their body weight into the push down direction. As outlined previously, the other main difference with the data collected by Stobbe (1982) was that the forces were measured at the distal end of the humerus or the proximal end of the forearm, so it was not a true representation of total arm strength.

The force direction that had the highest RMS error was the Push Forward condition (46.6 N) and the hand height condition that had the highest RMS error was the Overhead height (48.0 N). Again, the large RMS error in the overhead locations can partially be explained by the standing versus seated methodological difference between strength databases, however the large error in the push forward exertion is not so obvious. The force direction with the lowest RMS error in the comparison was Lateral condition (29.4 N) and the hand height with the lowest RMS error was at stature height, however it should be noted that the fewest amount of comparisons were done at Stature height as there was only data from 2 hand locations at this height (n=12).

It was also interesting that the peak errors did not necessarily agree with the average errors. Though there was a large tendency towards average errors being on the side of over-prediction, some of the largest peak errors were gross underestimations of strength by 3DSSPP. For example, when evaluating the hand heights, the highest peak error of -129 N was seen at the Overhead location, despite the average error being only 3.8 N. This trend was also observed when comparing force directions, as the push down direction had a peak error of -129 N, while the average error was only -13.3 N, the smallest of all force directions.

One of the primary underlying concerns with 3DSSPP's joint strength demands model is that the majority of the empirical data that went into the development of the predictive models of strength (Stobbe, 1982) were evaluated just distal to the humerus rather than at the hand. The strength estimations are based on three equations at the shoulder, one at the elbow and three at the wrist, so there is an increased potential for errors to propagate through the link segment model when determining the static joint moment and reaction forces based on forces and moments not physically measured at the hand. To add to the limitations, this thesis has shown that arm posture is very important when producing exertions at the hand, so if the posture prediction algorithms within 3DSSPP do not reflect the postures obtained by humans to maximize strength, even further errors may be seen compared to actual measured results. In this thesis, the comparisons were done using the 3DSSPP predicted postures with no manipulations made to the manikin to maintain consistency. Though it is possible to make manual manipulations to the predicted posture of the manikin, it takes a highly skilled ergonomist and much more time to accurately accomplish this, so there is a high probability that the raw posture predictions provided by 3DSSPP are being used in industry to make important ergonomic decisions. That being said, by manually manipulating the posture in this thesis, it is possible that some of the strength predictions could have been improved, but since the manikin was standing in a locked neutral posture and was only able to move its arms, the posture of the manikins visually appeared to be fairly consistent with the posture of the subjects in this thesis.

It is concerning that not only was 3DSSPP inaccurate in this comparison, but it tended to overpredict strength. 3DSSPP is one of the most popular ergonomic software options available, and a very large number of ergonomic decisions in industry are being based on its percent capable strength values. The fact that 3DSSPP might be overestimating many strengths, rather than being more conservative in its estimations, raises serious concerns over its effectiveness in the workplace. It is strongly suggested that the validity of 3DSSPP is further compared with more expansive empirical data, and to other ergonomic software packages such as Jack (Siemens, 2011) and Santos (SantosHuman™ Inc., University of Iowa) that include similar strength prediction models within their framework in order to further evaluate the strength prediction models incorporated in current digital human models.

5.4 Limitations and Future Considerations

There were some limitations of this study that would likely have to be addressed in future collections using this methodology. The first would be the amount of variation in shoulder position. In previous studies, it was assumed that, through verbal feedback and subject instructions, the relative location of the shoulder would remain fairly constant, however, as shown in Figure 4.5, it was discovered in this study that this is not necessarily the case, as the resultant within-subject shoulder location standard deviations ranged between 1.86 to 2.94 cm . It is suggested that ,in future studies, the subjects' torsos should be harnessed to the apparatus to limit shoulder movement. Though quantifying the movement of the shoulder in this study could have potentially helped with these errors as compared to Potvin et al. (2010), it would still be ideal to control for the posture of the torso to make sure certain subjects are not gaining any mechanical advantages over the others.

Another consideration in any future collections of this arm strength protocol is the importance of consistent verbal instructions and feedback between subjects. With the mentally complex task of exerting maximal forces while also controlling exertion direction based on visual feedback, the verbal instructions have the potential to influence the way in which the subjects weighed the force-accuracy trade off. It has been shown in previous research that force and torque production by the shoulder complex can be reduced by performing concurrent tasks, especially those involving a cognitively demanding component (Smets, Potvin, & Keir, 2009; MacDonell & Keir, 2005). MacDonell & Keir (2005) were the first to evaluate the interference effects of gripping and cognitive demands on the ability to perform maximal shoulder exertions in both flexion and abduction. They concluded that a mental task may interfere with physical exertions to the same, or greater, extent than performing a concurrent physical task, and that this should be an important consideration in future studies evaluating maximal muscular loading. Smets et al.

(2009) also observed that peak arm force was always greater when subjects did not have to mentally attend to a visual force target-matching task during a constrained gripping task. The authors suggested that a general correction factor for physical or mentally concurrent tasks could be determined for use with existing strength prediction models. This previous research suggests that controlling for, and/or limiting, the amount of cognitive complexity in developing threshold limit values should be something more thoroughly considered in the future. Some possible ways of combatting this cognitive complexity problem is to have the subjects become more familiar with the task. Research by Di Russo, Pitzalis, Aprile, & Spinelli (2005) has shown that, in specific groups who demonstrate a high level of specicifity and practice such as atheletes, the central nervous system adapts at the motor programming level to become more efficient. Experience at a task, in a group of experts, reduced neural activity in motor preperation, suggesting a more refined neural organization of the process (Di Russo et al., 2005).

One further suggestion in future research would be to include a standardized MVC at the beginning and end of each session during the data collection. This approach was utilized by Chow and Dickerson (2009) in order to determine whether fatigue occurred from the beginning to the end of the protocol by performing a t-test between the standardized exertions for every subject.

CHAPTER 6 - CONCLUSIONS

The main purpose of this thesis was to measure arm strengths in the 1D, 2D and 3D exertion directions and to determine whether including more specific arm posture information could improve regression equation predictions of arm strength. It was found that the strongest exertion directions, at each hand location, tended to be those that were in-line with the arm, highlighting the importance of the 3D moment arms of the force vectors from shoulder and elbow to the hand in determining arm strength.

In the comparison of regression models with and without postural information (M_{ALL} and M_{NP}, respectively), the M_{ALL} model performed better than the M_{NP} model by explaining 8.1% more variance and having a reduced RMS error of 1.4 N, confirming the hypothesized importance of the additional postural variables. The main inputs in the stepwise model that contributed to the better prediction in the M_{ALL} model were the shoulder and elbow 3D moment arms, as well as the radius vectors from the hand to the shoulder.

Not only were the extra postural variables shown to be important in the improvement of predictive strength equations, but they also highlighted how the subjects in the group may have been following some sort of movement strategy in order to maximize their strength. Further analysis in this regard could potentially lead to improvements in both strength and posture prediction models, when a task requiring arm strength is being analyzed. With the inverse relationship observed between strength and the resultant 3D moment arms, particularly those observed at the shoulder, it would be interesting to evaluate how humans tend to optimize arm strength based on various arm posture metrics. If there are general movement strategies and specific cost functions optimized by humans at the neural level, some insight into these strategies could become a valuable tool in the improvement of digital human models.

In the 3DSSPP comparison performed in this thesis, the overall correlation between 3DSSPP's 50th percentile capable values and empirical strength data was found to be low (r = 0.305). With an overall RMS error of 39 N, or approximately 4 kg, this is greater than 50% of the maximal acceptable force level at Ford Motor Company for one armed exertions, meaning any prediction that was given would have had an error larger than the mean itself. This result calls into question the real-world applicability of the University of Michigan Center for Ergonomics (2006) claim that the strength predictions provided by 3DSSPP correlate strongly (r=0.8) with the emperical strength database used in the software, mainly Stobbe (1982), Schanne (1972) and Clark (1966). The average errors were also found to be heavily weighted towards over-prediction by 3DSSPP, which disagrees with the traditional ergonomic perspective of keeping strength predictions conservative.

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Appendix A: Subject Information Sheet

Subject Number	Subject Name

Address		
	City:	**Postal Code:**
	Phone:	

Age	Height (m)	Mass (kg)

Handedness	**Right**
	Left

Have you ever experienced an Upper Extremity Injury?	**Yes**
	No

If Yes, please provide the date of the injury and any other specific details of the injury:

Appendix B: Letter of Information and Consent

June 28th, 2010

Letter of Information and Consent

An Investigation of arm postures during maximal shoulder exertions

Investigators: Dr. James Potvin & Nicholas LaDelfa

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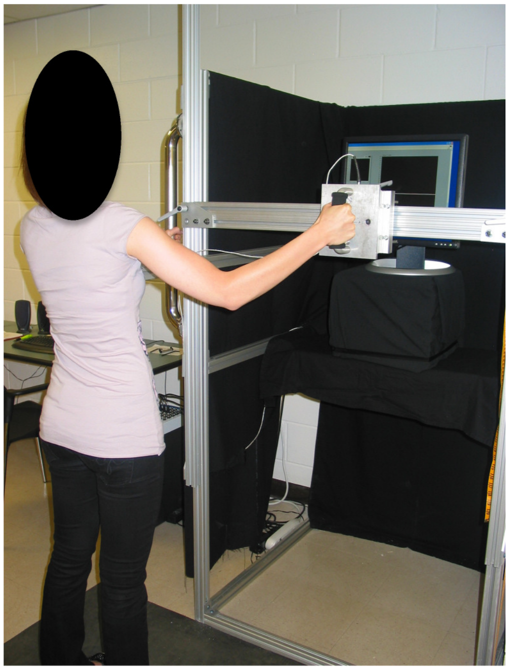
Purpose of the Study

The goal of this study will be to understand the arm postures that are adopted by humans as they perform shoulder exertions in a specific direction and hand location. It is hypothesized that monitoring the posture of the arm while performing multi-directional, maximal shoulder exertions may provide key pieces of information regarding the movement strategies adopted by humans. We believe accounting for these movement strategies and postures in our predictive shoulder strength equations will lead to a tighter correlation between predicted shoulder strength and actual measured shoulder strength. The direct applications and implications of this research includes the improvement of ergonomic tools that are in use today. Currently, very important ergonomic decisions regarding shoulder strength are being made based on somewhat inaccurate shoulder strength predictive software. This research will go a long way towards improving the validity of ergonomic tools, thus lowering the incidence of work-related shoulder injuries.

Procedures involved in the Research

Participation in this study will involve four sessions in the McMaster Occupational Biomechanics Laboratory in the Ivor Wynne Centre, room A108. Before study commencement, physical characteristics such as height, weight, age, and arm length will have to be measured. This data will be kept confidential.

You will stand in front of a slotted rail set up with the front of your body resting against a protruding padded pole that rests on the sternum, or chest bone. Your non-dominant hand will be gripping onto a vertical handlebar for support and balance. With your dominant hand, you will grip a padded handle that is mounted to a force plate also attached to the slotted rail testing apparatus. The force plate will be used to measure the three dimensional forces that you are exerting on the handle.



Kinematic sensors and motion capture cameras will be used to determine the posture of your dominant arm, which will be performing the exertions. Up to four kinematic sensors will be taped onto your arm and will be tracked in 3-D space by use of an electromagnetic source. This electromagnetic source is not felt at all and will put you at no risk whatsoever. The motion capture cameras also record the motion of little reflective markers that will also be taped onto your arm. These cameras will only emit and capture infrared light, therefore only the reflection off the markers are recorded, not any discernable video of yourself. This is the same motion capture technology that is used in the making of sports video games and animated movies.

During the protocol, you will be asked to apply as much force as possible (maximal voluntary efforts or MVEs) on a handle attached to the force plate that will be set in nine randomized positions. These positions are comprised of three heights (belly height, shoulder height, and head height) as well as at three angles (0°, 45°, and 90°). For each of the 9 hand positions, there will be up to 26 different exertion directions in 3D space. A very intuitive computer program will aid you in making sure you are pulling or pushing in the appropriate direction. Each effort will last for 3-5 seconds. In total, approximately 240 exertions will be completed during the study. In order to complete these exertions with adequate rest between trials, the entire protocol will occur in four, 1-hour testing sessions. Each testing session will involve 60 exertions that will be separated by approximately one-minute. It is important that you give a complete maximal effort to every one of the 60 exertions during each testing session. There will be at least three days of rest between subsequent testing days.

Potential Harms, Risks or Discomforts:

As this is a study that measures physical exertion and force production, there exists a possibility of localized muscle fatigue in the shoulder, upper arm, upper back and pectoral region. This would be due to the exertion of force and the recruitment of muscle to produce that force, similar to what may be felt after lifting weights at the gym. It should be noted that you will be in complete control of how much force is being applied or produced. Furthermore, you will be free to take a break or stop participating at any time if you feel uncomfortable or tired. You will be given ample rest between conditions and will be free to end a session if you feel it is necessary. It may be necessary for you to return for more than four sessions if you do not feel comfortable performing the current protocol as it is designed.

Potential Benefits

Although there will be no direct benefits to you, the study will have a lot of practical and theoretical applications. Benefits of participating in the study would be to experience first hand some of the methods and procedures used in conducting ergonomic research. As described above, benefits to the scientific community would be improvement of the ergonomic tools available to ergonomists in order to make more valid assessments that will hopefully reduce the incidence of work related shoulder injuries.

Payment or Reimbursement:

This study will pay subjects at an hourly rate of $15 per hour. The study protocol will require four, one-hour testing sessions, therefore each subject will receive $60 for their participation at the end of the study.

Confidentiality:

You will be assigned a randomly generated subject code known only to the investigators and therefore your identity can not be determined by anyone other than the investigators. Your personal information including name, age, and physical characteristics will be kept anonymous on all documents using the coding system. The information obtained in this study will be used for research purposes only and will be kept in a locked cabinet or stored on a password protected computer for a maximum of 10 years. As mentioned previously, the infrared cameras will only record the movement of the reflective markers so the subjects' confidentiality will be maintained.

Participation:

Your participation in this study is strictly voluntary. If you choose to volunteer, you have the right to withdraw from the study without any consequence at any time either before or during the testing sessions. If you choose to withdraw, all of your digital data will be permanently deleted from the computers and all paperwork will be shredded. If you choose to withdraw prior to completion of the study, compensation will be pro-rated for your time based on the hourly rate of $15 per hour. Should you have to return to the lab for a 5th session, you will also be paid for your time at an hourly rate of $15 per hour.

Information about the Study Results:

You may obtain information about the results of the study by contacting one of the investigators or by leaving your email address on a confidential form to which the final results will be mailed.

Information about Participating as a Study Subject:

If you have questions or require more information about the study itself, please contact Nicholas LaDelfa.

This study has been reviewed and has received ethics clearance from the McMaster Research Ethics Board. If you have concerns or questions about your rights as a participant or about the way the study is conducted, you may contact:

McMaster Research Ethics Board Secretariat

Telephone: (905) 525-9140 ext. 23142

c/o Office of Research Services

E-mail: ethicsoffice@mcmaster.ca

CONSENT

I have read the information presented in the information letter about the study being conducted by Dr. Potvin and Nicholas LaDelfa at McMaster University. I have had the opportunity to ask questions about my involvement in this study, and to receive any additional details I wanted to know about the study. I understand that I may withdraw from the study at any time, if I choose to do so, and I agree to participate in this study. I have been given a copy of this form.

____

Name of Participant

Appendix C: Strength and Kinematic Data

Table C.1: Average resultant strengths for each exertion direction and hand location. Green cells indicate the maximum at each hand location, with the bolded being the highest overall strength and red cells indicate the minimum at each hand location, with the bolded being the lowest overall strength (n=17).

Direction	Overhead		Shoulder			Umbilicus		
	0 deg	45 deg	0 deg	45 deg	90 deg	0 deg	45 deg	90 deg
Up	48.2	51.0	56.4	54.0	45.6	82.1	68.1	67.6
Down	79.4	60.7	78.8	58.7	55.5	80.2	70.3	63.2
Push	89.8	58.8	113.6	67.5	40.0	99.4	72.1	54.6
Pull	85.0	56.7	**135.4**	76.0	38.0	119.9	73.2	44.0
Left	55.8	53.5	71.7	79.0	109.6	64.6	69.3	104.9
Right	47.2	50.8	56.9	61.2	91.7	48.7	52.8	88.2
Up/Push	114.1	81.3	86.3	66.7	47.4	73.4	59.3	50.7
Up/Pull	41.6	42.5	67.2	51.6	**35.9**	106.7	70.2	47.4
Up/Left	47.8	46.3	58.4	57.1	51.7	69.4	70.4	92.1
Up/Right	43.8	55.2	45.9	51.2	56.9	51.6	49.6	49.4
Down/Push	61.6	47.9	71.4	56.0	43.8	90.8	73.4	57.6
Down/Pull	112.8	82.0	115.3	73.7	53.6	73.7	54.7	52.3
Down/Left	59.8	75.6	65.6	64.9	83.5	60.5	57.2	54.8
Down/Rigt	57.8	49.8	64.1	55.3	53.0	56.2	59.1	79.8
Push/Left	58.8	53.8	72.6	53.1	57.8	75.1	59.1	61.5
Push/Right	60.5	58.3	72.2	75.1	44.9	65.6	73.9	62.7
Pull/Left	56.4	68.7	86.2	96.7	56.9	81.4	88.4	61.6
Pull/Right	60.3	49.2	73.4	49.9	46.8	65.4	47.7	42.2
Up/Push/Left	82.7	65.5	80.0	70.2	51.3	81.6	71.2	68.3
Up/Push/Right	83.6	107.1	72.0	90.5	57.6	64.9	68.2	58.1
Up/Pull/Left	51.1	53.0	72.3	70.4	52.7	112.3	109.4	80.6
Up/Pull/Right	51.0	47.9	62.8	53.6	47.2	88.1	55.5	48.2
Down/Push/Left	62.9	59.3	74.1	59.4	62.3	85.0	72.7	58.6
Down/Push/Right	63.0	54.2	70.4	69.5	49.0	79.5	87.3	67.4
Down/Pull/Left	91.8	114.0	110.0	112.6	77.8	73.6	74.0	58.3
Down/Pull/Right	94.6	67.0	86.9	63.4	55.1	68.9	61.5	59.6
Mean	68.2	62.1	77.7	66.9	56.4	77.7	68.1	63.1
St.Dev	30.0	27.4	34.0	27.3	27.8	36.3	24.7	29.2

Table C.2: Average elbow angle in degrees for each exertion direction and hand location (n=17).

Direction	Overhead		Shoulder			Umbilicus		
	0 deg	**45 deg**	**0 deg**	**45 deg**	**90 deg**	**0 deg**	**45 deg**	**90 deg**
Up	127.9	133.9	95.4	123.0	131.4	108.0	111.6	116.0
Down	124.2	133.1	104.0	129.5	132.8	122.2	125.3	124.3
Push	139.2	137.3	111.2	125.8	132.8	113.7	114.7	117.5
Pull	125.5	135.0	101.7	126.2	144.9	110.1	116.2	128.1
Left	126.4	138.3	100.3	129.2	134.9	112.2	116.0	118.4
Right	127.6	142.2	101.3	134.6	142.7	113.8	119.7	124.9
Up/Push	135.5	133.5	97.5	124.5	127.6	107.6	112.1	116.5
Up/Pull	127.4	138.1	96.7	124.5	137.5	107.8	112.7	120.8
Up/Left	125.6	132.1	95.7	121.8	130.0	109.5	114.2	117.5
Up/Right	127.7	139.9	97.0	128.9	132.7	107.7	114.2	119.4
Down/Push	132.8	135.0	104.4	128.6	130.8	123.0	123.6	121.5
Down/Pull	123.1	130.4	97.7	124.6	138.3	116.9	120.8	126.7
Down/Left	122.0	131.1	101.8	128.1	130.1	118.4	120.9	121.2
Down/Rigt	123.8	134.1	97.4	129.4	136.5	118.1	125.8	130.9
Push/Left	130.9	132.1	105.9	127.3	133.3	114.0	115.5	117.9
Push/Right	134.3	138.4	109.3	130.8	132.9	115.5	118.5	120.3
Pull/Left	124.9	137.0	102.3	125.8	139.1	111.9	115.2	123.3
Pull/Right	125.1	140.4	99.8	129.4	144.5	112.0	122.0	126.7
Up/Push/Left	128.1	130.7	98.8	120.4	129.6	107.5	112.4	116.1
Up/Push/Right	135.7	140.6	101.4	127.2	131.2	106.9	112.7	116.6
Up/Pull/Left	127.9	135.3	96.9	124.8	135.4	109.8	114.8	119.0
Up/Pull/Right	125.2	138.8	96.1	128.1	140.3	107.2	115.5	122.1
Down/Push/Left	126.8	134.3	104.5	126.7	131.7	121.1	119.8	120.0
Down/Push/Right	128.2	134.0	103.0	132.1	133.5	122.3	124.9	123.9
Down/Pull/Left	123.0	135.8	98.8	123.8	134.9	118.3	120.4	123.4
Down/Pull/Right	120.2	136.2	97.3	125.6	136.4	117.0	119.6	130.1
Mean	127.7	135.7	100.6	127.0	134.8	113.6	117.7	121.7
St.Dev	4.6	3.2	4.1	3.2	4.6	5.3	4.4	4.3

Table C.3: Average horizontal shoulder angle in degrees for each exertion direction and hand location (n=17).

Direction	Overhead		Shoulder			Umbilicus		
	0 deg	45 deg	0 deg	45 deg	90 deg	0 deg	45 deg	90 deg
Up	72.0	40.6	76.6	38.1	3.2	49.8	24.1	21.3
Down	74.5	41.3	76.0	40.5	4.5	56.1	27.7	34.2
Push	71.8	35.2	74.1	34.4	7.0	51.7	19.1	37.5
Pull	55.9	29.2	66.2	28.1	5.6	51.0	17.4	28.1
Left	67.6	38.2	67.4	38.8	6.2	42.8	26.8	32.9
Right	59.2	36.6	57.8	36.2	6.0	44.6	34.9	13.2
Up/Push	77.2	40.8	78.5	36.6	4.3	54.0	21.0	36.0
Up/Pull	64.0	34.9	71.3	31.8	3.8	51.7	20.6	23.0
Up/Left	70.3	40.1	74.0	36.3	3.9	54.1	25.3	31.8
Up/Right	62.1	39.2	68.7	37.0	4.6	49.8	33.8	23.0
Down/Push	70.6	40.6	72.8	39.3	5.9	57.9	22.6	36.8
Down/Pull	71.5	34.4	77.0	33.3	7.1	58.3	20.3	32.9
Down/Left	73.5	45.2	80.8	44.0	4.2	52.1	27.9	32.2
Down/Rigt	65.6	35.1	63.2	35.8	4.8	53.4	27.1	24.5
Push/Left	71.9	36.4	72.9	38.2	6.2	49.0	20.5	32.2
Push/Right	67.5	36.0	69.5	40.2	5.7	57.7	33.3	31.9
Pull/Left	63.2	31.9	74.4	35.6	5.1	56.7	23.1	34.9
Pull/Right	57.7	33.3	52.9	30.4	4.7	42.9	19.1	23.7
Up/Push/Left	71.7	37.3	74.4	36.9	5.4	42.2	24.3	36.9
Up/Push/Right	68.6	41.6	71.1	40.0	4.4	49.9	25.1	34.0
Up/Pull/Left	64.5	36.4	70.4	34.8	5.0	60.0	22.0	27.7
Up/Pull/Right	57.7	35.1	60.1	33.0	3.8	44.9	21.8	19.6
Down/Push/Left	76.4	44.6	78.4	42.4	5.3	51.8	24.3	34.9
Down/Push/Right	70.2	39.8	70.0	40.5	6.2	58.6	34.7	31.1
Down/Pull/Left	77.1	42.6	83.0	40.9	6.5	59.0	28.2	36.3
Down/Pull/Right	61.2	34.0	61.8	31.3	7.3	47.9	19.7	25.0
Mean	67.8	37.7	70.9	36.7	5.3	51.8	24.8	29.8
St.Dev	6.2	3.9	7.2	3.9	1.1	5.4	5.0	6.4

Table C.4: Average vertical shoulder angle in degrees for each exertion direction and hand location (n=17).

Direction	Overhead		Shoulder			Umbilicus		
	0 deg	45 deg	0 deg	45 deg	90 deg	0 deg	45 deg	90 deg
Up	100.6	98.9	51.7	65.1	66.4	10.3	16.6	20.8
Down	96.8	96.5	49.1	65.2	65.7	13.1	19.3	24.7
Push	104.0	103.1	59.0	69.0	68.8	12.2	23.3	27.9
Pull	108.9	102.8	56.8	70.8	72.1	9.8	24.6	27.2
Left	101.2	100.9	58.5	67.9	67.6	16.1	20.4	22.1
Right	105.4	101.5	62.9	70.1	70.4	18.3	20.3	19.7
Up/Push	103.4	99.4	52.9	66.6	65.5	10.2	20.8	24.3
Up/Pull	106.4	101.4	54.4	69.0	68.8	11.3	20.4	22.9
Up/Left	100.4	97.2	54.0	65.3	65.4	11.7	17.2	22.7
Up/Right	105.5	101.4	56.3	68.7	67.5	14.6	16.8	20.5
Down/Push	96.2	98.2	54.4	66.3	65.8	14.4	21.9	32.3
Down/Pull	96.2	97.6	49.7	64.2	69.4	10.9	21.3	26.7
Down/Left	96.8	95.8	52.2	64.1	64.7	15.7	18.5	22.2
Down/Rigt	98.5	98.1	53.9	65.7	67.0	13.2	19.6	23.7
Push/Left	102.1	100.1	59.1	67.2	67.5	15.4	22.9	26.3
Push/Right	103.2	101.1	59.2	66.7	67.7	13.6	18.8	23.1
Pull/Left	101.9	103.8	55.1	66.9	70.0	11.0	18.3	27.2
Pull/Right	106.6	101.7	62.2	69.2	71.3	14.0	25.0	25.7
Up/Push/Left	101.0	98.4	55.1	64.1	65.7	12.0	18.9	25.4
Up/Push/Right	104.1	102.0	57.6	66.2	66.0	10.3	17.1	22.8
Up/Pull/Left	103.6	100.1	52.9	67.6	68.1	10.2	17.4	22.3
Up/Pull/Right	107.1	101.5	59.2	69.5	69.6	14.7	22.0	22.5
Down/Push/Left	97.1	97.3	53.7	63.9	66.4	15.9	22.2	27.1
Down/Push/Right	98.6	96.3	54.1	65.2	67.3	14.5	17.5	24.7
Down/Pull/Left	94.9	96.9	51.0	61.5	67.1	13.4	17.1	25.5
Down/Pull/Right	100.5	99.5	54.9	65.0	68.1	12.7	23.1	26.3
Mean	101.6	99.7	55.4	66.6	67.7	13.1	20.1	24.5
St.Dev	3.9	2.3	3.5	2.3	1.9	2.2	2.5	2.8

Appendix D: 3DSSPP Results

Table D.1 (presented on the next two pages): Full results from the 3DSSPP comparison analysis. Studies 1, 2A and 2B are from Potvin et al. (2010) and study 3 represents the current thesis. All hand locations were converted to the convention used in 3DSSPP. For each 1D exertion direction, the limiting joint, 50th percentile force (N), limiting moment (N.m) and limiting muscle effect are presented.

				3DSSPP Hand Positions (cm)			lift				push down				push forward			
Study	Height	Orient.	Angle	Horizontal	Vertical	Lateral	Limiting Joint	50% capable force (N)	Limiting Moment (Nm)	Limiting Muscle effect	Limiting Joint	50% capable force (N)	Limiting Moment (Nm)	Limiting Muscle effect	Limiting Joint	50% capable force (N)	Limiting Moment (Nm)	Limiting Muscle effect
2B	Waist	Hor	0	26.2	97.5	15.6	S	110.5	18.1	LAT	E	105	21.6	EXT	S	74.5	18.1	LAT
2B		Vert	0	26.2	97.5	15.6	W	127.5	8.2	RDLDEV	E	90.5	22.3	EXT	S	92.5	15.9	LAT
2B		Hor	45	18.8	97.5	33.5	W	142.5	5.9	EXT	S	105	16.4	MED	S	106	43.7	FWD
2B		Vert	45	18.8	97.5	33.5	W	156	8.2	RDLDEV	S	88.5	12.4	MED	S	104.5	44.6	FWD
2B		Hor	90	1.0	97.5	40.8	W	161.5	5.9	EXT	S	76	10.3	MED	S	107	41.7	FWD
2B		Vert	90	1.0	97.5	40.8	W	147.5	5.9	EXT	S	32.5	4.2	MED	S	120.5	42.5	FWD
1	Umbilicus	Vert	-20	27.6	105.1	-4.4	W	107.5	8.2	RDLDEV	E	80.5	23.2	EXT	S	113.5	40.1	ABD
1		Vert	0	3.1	105.1	15.6	W	121.5	8.2	RDLDEV	E	90.5	23.4	EXT	W	149	5.9	EXT
1		Vert	0	34.3	105.1	15.6	W	126	8.2	RDLDEV	E	89	22.2	EXT	W	169	5.9	EXT
1		Vert	45	7.1	105.1	21.7	W	127.5	8.2	RDLDEV	E	94	23.3	EXT	W	176	5.9	EXT
1		Vert	45	24.5	105.1	39.1	W	124.5	5.9	EXT	S	70	12.2	MED	S	107	44.5	FWD
1		Vert	90	1.0	105.1	21.8	W	136	8.2	RDLDEV	E	99	23	EXT	S	175.5	44.7	ADD
1		Vert	90	1.0	105.1	48.9	W	117	5.9	EXT	S	14.5	1.6	MED	S	31.5	1.6	MED
1	Shoulder	Vert	0	24.7	138.6	15.6	W	115	5.9	EXT	W	154	7.6	FLEX	E	90	24.8	EXT
2A		Hor	0	37.0	138.6	15.6	W	88.5	5.9	EXT	S	113.5	28.2	MED	E	92.5	22.1	EXT
2A		Vert	0	37.0	138.6	15.6	S	102.5	33.9	ABD	S	138.5	28.6	MED	E	96	22.6	EXT
1		Vert	0	48.2	138.6	15.6	S	67.5	36.1	ABD	S	112.5	40.7	ADD	E	112	20.2	EXT
1		Vert	45	18.2	138.6	32.8	W	97.5	5.9	EXT	S	48	7.7	MED	S	95	7.7	MED
2A		Hor	45	26.2	138.6	40.9	W	85.5	5.9	EXT	S	42	9.6	MED	S	121	9.6	MED
2A		Vert	45	26.2	138.6	40.9	W	99	5.9	EXT	S	45	9	MED	S	81	9	MED
1		Vert	45	34.4	138.6	49.0	S	68.5	36.2	ABD	S	100.5	35.4	ADD	S	141.5	42.8	FWD
1		Vert	90	1.0	138.6	39.2	W	99	5.9	EXT	W	133	7.6	FLX	W	165	7.6	FLX
1		Vert	90	1.0	138.6	62.8	S	94	46.8	ABD	S	8.5	0.3		S	5	0.2	
1	Eye	Vert	-20	39.8	156.6	-4.4	S	68	37	ABD	S	138.5	52.1	ADD	E	72.5	19.8	EXT
1		Vert	0	23.2	156.6	15.6	W	110.5	5.9	EXT	W	148	7.6	FLX	E	81.5	22.3	EXT
1		Vert	0	44.6	156.6	15.6	S	69.5	35.7	ABD	S	119	40.6	ADD	E	83.5	19.3	EXT
1		Vert	45	19.0	156.6	33.6	W	114	5.9	EXT	S	130.5	23.5	MED	S	121	23.5	MED
1		Vert	45	31.8	156.6	46.4	S	71	35.6	ABD	S	107	34.8	ADD	S	135	25.9	MED
1		Vert	90	1.0	156.6	15.8	E	68.5	22.8	EXT	E	115	32.8	FLX	W	164	7.6	FLX
1		Vert	90	1.0	156.6	59.2	S	98	45.9	ABD	S	114	37.3	ADD	S	98	39.7	FWD
2A		Hor	45	31.0	159.3	36.3	S	92.5	33.9	ABD	S	112	25.9	MED	S	143.5	25.9	MED
2A		Vert	45	31.0	159.3	36.3	S	88	34.5	ABD	S	127	26.4	MED	S	135.5	26.4	MED
2A	Stature	Hor	0	31.0	168.3	15.6	W	109	5.9	EXT	S	133	28.3	MED	E	89	19.2	EXT
2A		Vert	0	31.0	168.3	15.6	S	111	34.2	ABD	S	150.5	28.5	MED	E	78.5	19.5	EXT
2B	Overhead	Hor	0	11.0	185.9	15.6	E	62.5	16.1	EXT	E	150	33.4	FLX	S	93	32.1	FWD
2B		Vert	0	11.0	185.9	15.6	E	72.5	16.4	EXT	S	26.5	1.4	MED	S	6.5	1.3	MED
3		Vert	0	44.2	165.6	19.7	S	70	35.9	ABD	S	115	39.8	ADD	E	85	18.3	EXT
3		Vert	45	35.6	164.3	45.3	S	67.5	36.3	ABD	S	99.5	35.2	ADD	S	131.5	40.2	FWD
3	Shoulder	Vert	0	44.6	141.3	17.4	S	76	35.2	ABD	S	122	39.3	ADD	E	103	21.1	EXT
3		Vert	45	39.3	141.6	47.7	S	64	36.7	ABD	S	93.5	35.8	ADD	S	147.5	43	FWD
3		Vert	90	8.6	141.2	66.2	S	64	39.9	ABD	S	83	35.4	ADD	S	78	23.1	MED
3	Umbilicus	Vert	0	34.2	107.8	16.3	W	124.5	8.2	RDLDEV	E	88.5	22.3	EXT	S	171	25	LAT
3		Vert	45	28.1	108.6	37.9	W	120.5	5.9	EXT	S	72	13.1	MED	S	112	44.6	FWD
3		Ver	90	8.1	108.4	49.5	W	119	5.9	EXT	S	25.5	3.9	MED	S	50.5	3.9	MED

				3DSSPP Hand Positions (cm)			pull back				exert left				exert right			
Study	**Height**	**Orient.**	**Angle**	Horizontal	Vertical	Lateral	Limiting Joint	50% capable force (N)	Limiting Moment (Nm)	Limiting Muscle effect	Limiting Joint	50% capable force (N)	Limiting Moment (Nm)	Limiting Muscle effect	Limiting Joint	50% capable force (N)	Limiting Moment (Nm)	Limiting Muscle effect
2B	Waist	Hor	0	26.2	97.5	15.6	S	115	25.3	MED	S	104.5	36.2	ADD	S	78.5	33.5	ABD
2B		Vert	0	26.2	97.5	15.6	S	108	38.5	BACK	S	95	36.3	ADD	S	64.5	15.9	LAT
2B		Hor	45	18.8	97.5	33.5	S	89	35	BACK	S	100.5	36.3	ADD	S	92.5	42.4	ABD
2B		Vert	45	18.8	97.5	33.5	S	104.5	35.6	BACK	S	53	12.3	MED	W	94.5	5.9	EXT
2B		Hor	90	1.0	97.5	40.8	S	77	10.3	MED	S	49.5	10.3	MED	E	103	20.8	EXT
2B		Vert	90	1.0	97.5	40.8	E	95	21.3	EXT	S	20	4.2	MED	W	91	5.9	EXT
1	Umbilicus	Vert	-20	27.6	105.1	-4.4	S	140.5	26.2	MED	S	107	26.2	MED	W	99.5	5.9	EXT
1		Vert	0	3.1	105.1	15.6	S	49	7.3	MED	S	30.5	7.3	MED	W	93	5.9	EXT
1		Vert	0	34.3	105.1	15.6	S	162.5	39.3	BACK	S	123	27.3	MED	W	104.5	5.9	EXT
1		Vert	45	7.1	105.1	21.7	S	64.5	7.9	MED	S	33.5	7.9	MED	W	91.5	5.9	EXT
1		Vert	45	24.5	105.1	39.1	S	92.5	35.6	BACK	S	55.5	12.1	MED	W	99	5.9	EXT
1		Vert	90	1.0	105.1	21.8	S	51	6.2	MED	S	26	6.2	MED	W	89.5	5.9	EXT
1		Vert	90	1.0	105.1	48.9	S	91.5	32.6	BACK	S	13.5	1.5	MED	W	112.5	5.9	EXT
1	Shoulder	Vert	0	24.7	138.6	15.6	W	121.5	8.2	RDLDEV	W	139	7.5	FLX	W	104	5.9	EXT
2A		Hor	0	37.0	138.6	15.6	W	139.5	8.2	RDLDEV	S	119.5	42.1	FWD	S	105	35.5	BACK
2A		Vert	0	37.0	138.6	15.6	W	139.5	8.2	RDLDEV	S	136	43.5	FWD	W	109	5.9	EXT
1		Vert	0	48.2	138.6	15.6	W	179.5	8.2	RDLDEV	S	96.5	43.8	FWD	S	84	36.8	BACK
1		Vert	45	18.2	138.6	32.8	W	192	5.9	EXT	S	82	7.8	MED	E	92.5	24.4	EXT
2A		Hor	45	26.2	138.6	40.9	S	142.5	32.8	BACK	W	115	8.1	RDLDEV	E	76	22.1	EXT
2A		Vert	45	26.2	138.6	40.9	S	162.5	34.2	BACK	S	76.5	9	MED	E	83.5	22.7	EXT
1		Vert	45	34.4	138.6	49.0	S	119	34.7	BACK	W	131.5	8.2	RDLDEV	E	83	20.4	EXT
1		Vert	90	1.0	138.6	39.2	W	122.5	5.9	EXT	W	116.5	8.2	RDLDEV	E	85.5	24.7	EXT
1		Vert	90	1.0	138.6	62.8	S	88.5	33.4	BACK	S	125.5	0.4	MED	E	108.5	21.2	EXT
1	Eye	Vert	-20	39.8	156.6	-4.4	W	120	8.2	RDLDEV	S	102	26.6	MED	W	89	5.9	EXT
1		Vert	0	23.2	156.6	15.6	W	132	8.2	RDLDEV	S	169	39.5	FWD	S	143	33.3	BACK
1		Vert	0	44.6	156.6	15.6	W	144.5	8.2	RDLDEV	S	94.5	41.7	FWD	S	79	34.6	BACK
1		Vert	45	19.0	156.6	33.6	W	106	5.9	EXT	W	120	8.1	RDLDEV	E	75	22.2	EXT
1		Vert	45	31.8	156.6	46.4	S	112	32.4	BACK	W	114	8.2	RDLDEV	E	66	19.4	EXT
1		Vert	90	1.0	156.6	15.8	W	127.5	5.9	EXT	W	101	5.9	EXT	W	130	7.6	FLX
1		Vert	90	1.0	156.6	59.2	S	76	30.4	BACK	W	131	8.2	RDLDEV	E	78	19.9	EXT
2A		Hor	45	31.0	159.3	36.3	W	126.5	5.9	EXT	W	115.5	8.2	RDLDEV	E	66.5	20.1	EXT
2A		Vert	45	31.0	159.3	36.3	W	119	5.9	EXT	W	119	8.2	RDLDEV	E	70	20.3	EXT
2A	Stature	Hor	0	31.0	168.3	15.6	W	119.5	5.9	EXT	S	105.5	38.2	FWD	S	83	30.9	BACK
2A		Vert	0	31.0	168.3	15.6	S	120	34.2	ABD	S	110	39.2	FWD	S	89	32.2	BACK
2B	Overhead	Hor	0	11.0	185.9	15.6	S	61	22.1	BACK	S	103	44.1	ABD	E	85	16.2	EXT
2B		Vert	0	11.0	185.9	15.6	S	61	24.1	BACK	S	87	44.1	ABD	S	16.5	1.4	MED
3		Vert	0	44.2	165.6	19.7	S	133.5	36.1	ABD	S	87.5	40.7	FWD	S	71.5	33.5	BACK
3		Vert	45	35.6	164.3	45.3	S	103.5	31.8	BACK	S	109	40.3	FWD	E	61.5	18.1	EXT
3	Shoulder	Vert	0	44.6	141.3	17.4	W	160	8.2	RDLDEV	S	106	43.5	FWD	S	93	36.7	BACK
3		Vert	45	39.3	141.6	47.7	S	123	34.8	BACK	S	116.5	42.8	FWD	E	81.5	19.9	EXT
3		Vert	90	8.6	141.2	66.2	W	79.5	5.9	EXT	W	182.5	8.2	RDLDEV	E	118.5	20.4	EXT
3	Umbilicus	Vert	0	34.2	107.8	16.3	S	160.5	38.9	BACK	S	118.5	26.9	MED	W	103	5.9	EXT
3		Vert	45	28.1	108.6	37.9	S	97.5	36	BACK	S	59.5	13.1	MED	W	99.5	5.9	EXT
3		Ver	90	8.1	108.4	49.5	S	89.5	33.6	BACK	S	23.5	3.9	MED	W	110	5.9	EXT