The Effect of Hand Dominance on Manual Arm Strength

by

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The above committee determined that the thesis is acceptable in form and content and that a satisfactory knowledge of the field covered by the thesis was demonstrated by the candidate during an oral examination. A signed copy of the Certificate of Approval is available from the School of Graduate and Postdoctoral Studies.

ABSTRACT

In the design of manual work tasks, considering task demands in the context of human strength capability has been vital to assessing workplace musculoskeletal injury risk. This is particularly true for the upper extremities, which are often relied upon to produce manual forces in most occupational manufacturing tasks. Despite workers commonly utilizing both limbs in the workplace, the effect of hand dominance on any type of upper extremity strength is relatively underexplored. In several ergonomics models of strength capacity, the non-dominant hand is assumed to be approximately 10% weaker than the dominant hand, but this heuristic is primarily based on grip strength data and does not account for potential differences between handedness (i.e. left- vs right-handers) and sex (males vs females). As such, the purpose of this research is to examine how manual arm strength differs between the dominant and non-dominant limbs in a sample of right and left-handed males and females.

Keywords: hand dominance; manual arm strength; upper extremity; handedness; strength

AUTHOR'S DECLARATION

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__________________________________ FAHIMA WAKEELY

STATEMENT OF CONTRIBUTIONS

The work described in Chapters 3 and 4 was performed within the Occupational Neuromechanics and Ergonomics Laboratory at Ontario Tech University, using equipment and software designed by Ryan Foley and Dr. Nicholas La Delfa. Data collection was primarily conducted by myself, Michael Watterworth and Sarah Norman. Under the regular advisement of Dr. La Delfa, I conducted all data synthesis, statistical analyses and primary interpretation of results. Dr. La Delfa provided feedback and made minor editorial adjustments to the manuscripts contained within.

I, Fahima Wakeely, hereby certify that I am the sole author of this thesis. I have used standard referencing practices to acknowledge ideas, research techniques, or other materials that belong to others. Furthermore, I hereby certify that I am the sole source of the creative works and/or inventive knowledge described in this thesis.

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LIST OF ABBREVIATIONS AND SYMBOLS

NIOSH	National Institute of Occupational Safety and Health
WMSDs	Work-Related Musculoskeletal Disorders
IJASS	Independent Joint Axis Static Strength
ISB	International Society of Biomechanics
TLV	Threshold Limit Value
MAS	Manual Arm Strength
DHM	Digital Human Model
AFF	Arm Force Field

Chapter 1. Thesis Introduction

In the field of ergonomics, estimation of manual arm strength, or the maximum force that can be produced by the arm with the hand as the end-effector, is commonly used to help set acceptable loads in industry (La Delfa & Potvin, 2017). This is done to ensure the strength demands required of a particular task do not exceed the strength capabilities of approximately 75% of the population (Snook, 1978; Waters et al., 1993). The Arm Force Field (AFF) method has shown initial promise in comparison to traditional ergonomics approaches for estimating acceptable strength (Hall et al., 2021). However, there are still several gaps in knowledge that are needed to further improve upon this method. For example, much of the data contained within strength-based ergonomics assessments tools only include one-handed strength measures from the dominant limb. This is not indicative of many occupation scenarios where the non-dominant limb is involved in the task. The current assumption is that the non-dominant limb has approximately 90-95% strength of the dominant limb; however, there is little evidence supporting the validity of this assumption (Demura, Miyaguchi, & Aoki, 2010). Furthermore, there are consistent differences shown between the strength asymmetry of right- and left-handed individuals; whereby left-handed individuals generally have more balanced strength between their dominant and non-dominant sides, but normative strength databases are saturated with primarily right-handed data. There is good reason for this omission, given left-handers typically make up 10-13% of the overall population. Nonetheless, this still remains an important consideration that is generally ignored in the ergonomics literature (McCarthy & Richter, 2020).

This thesis will begin with a comprehensive narrative literature review that focuses on strength prediction in ergonomics and the available evidence on the effects of handedness on various biomechanical outcomes, including strength. This review will focus on current gaps in the literature and set the stage for an experimental study that forms the basis of this thesis.

Chapter 3 is a laboratory study that examines how manual arm strength differs between dominant and non-dominant limbs. This study touches on differences between handedness groups, as well as sex. Furthermore, this study also incorporates joint-level kinematic and kinetic analyses to examines some of the underlying neuromechanical strategies that may explain some of the observed differences in strength. The study of hand dominance with respect to manual arm strength capability can provide fundamental shift in how acceptable manual forces are utilized and estimated in industry. The hope is that research can be built upon and eventually incorporated into ergonomics methods utilized by practitioners to refine their estimates of manual force capability and injury risk.

1. Research Questions

1) What are the differences in manual arm strength between the dominant and non-dominant upper limbs of right- and left-handed males and females?

2) What are the corresponding differences in joint moments between the dominant and non-dominant limbs of right- and left-handed males and females during manual arm strength exertions?

2. Hypotheses

The following hypotheses were tested, where H_O represents the null hypothesis, and H_A represents an alternative hypothesis:

1) H_O: Right-handed and left-handed individuals will have the same discrepancy in manual arm strength between limbs

H_A: Right-handed individuals will have a greater discrepancy in dominant vs non-dominant arm manual arm strength compared to left-handed individuals

2) H_O: Males and females will have no difference in strength between arms

H_A: Males and females will have difference in strength between arms

3) H_O: There will be no differences in joint moments between dominant and non-dominant limbs during manual strength exertions

H_A: Joint moments of dominant arm will be more pronounced in comparison to the non-dominant arm.

3. References

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Chapter 2. The role of handedness in ergonomics strength analyses: A Review of Literature

1. Strength Predictions in Ergonomics

Ergonomics guidelines and thresholds for physical tasks such as lifting, lowering, pushing and pulling have been determined by studies evaluating upper limb injury risks (Garg et al., 2012). The National Institute of Occupational Safety and Health (NIOSH) developed an ergonomic assessment tool in 1991 which incorporates TLV's for manual lifting tasks (Waters et al., 1993). Throughout the years, these recommended weight limit guidelines for manual tasks have been modified due to improved understanding of the biomechanical, physiological, and psychophysical constraints of population and work environments. Setting limits are important when it comes to the demands placed on the human body, which is why developing valid guidelines have been a point of such research emphasis.

A common ergonomics approach for determining acceptable force demands in the workplace is to compare occupational task demands to research-based estimates of human strength capability (Mital & Kumar, 1998). Maximum strength capability can be used in combination with psychophysically-derived estimates of physical exertion to estimate threshold limit values (TLVs) for work related tasks (Ciriello & Snook, 1999; Ciriello, Snook, Hashemi, & Cotnam, 1999; Mital & Kumar, 1998; Potvin, Chiang, McKean, & Stephens, 2000). TLVs are based on equations that determine maximal acceptable efforts of the upper extremity, specifically the hand/wrist, elbow, and shoulder.

1.1. Joint Strength Testing

Strength is typically categorized by two states of exertion: static and dynamic. Static strength refers to when force exertions are produced while the muscle stays constant in length (no movement), also referred to as isometric strength (Caldwell et al., 1974). However, various tasks performed in the workplace require dynamic motion of the upper limb. Dynamic strength refers to the maximum force output when muscle length is changing. A sub-classification of dynamic strength is isokinetic strength, which is when exertions are produced while the muscle length is changing at a constant velocity (Caldwell et al., 1993). Isokinetic strength testing is when the movement velocity is constant, which allows for a more controlled environment yielding results that are simpler to evaluate rather than looking at muscle strength under more complex dynamic conditions (Ly & Handelsman, 2002, Verdijk et al., 2009, Sandra et al., 2010, Stark et al., 2011). Isokinetic strength measures are usually evaluated with torque, allowing for an appropriate assessment of strength and functional ability (Stark et al., 2011). Another sub-classification of dynamic strength is isotonic strength, which is measured when constant tension is held in the muscle throughout the movement (Sandra et al., 2010). In isotonic testing, the muscle can be contracting either eccentrically or concentrically while maintaining a constant load throughout the contraction. Isotonic contractions are much easier on the joints as it activates the muscles without the additional stress. Therefore, isotonic strength testing has a greater training effect as it is focused more on the acquired movement than muscle building (Salter, 1955).

Mcdonald et al., (2018) conducted a thorough investigation evaluating shoulder strength while modifying posture, velocity, and exertion direction during isometric and isokinetic exertions. Maximal shoulder flexion and extension exertions were elicited across different movement planes, angular velocities, and grip types. The data were collected to determine the relationship between isometric and isokinetic strength and to evaluate the efficacy of the predictive equations that were used to calculate strength. Measuring joint strength while utilizing dynamic strength measurements is seen as a more valid assessment as it mimics the conditions of the workplace. However, researchers found that isometric strength measurements are a more efficient method and have less variability compared to dynamic strength measures (Romero-Franco et al., 2019; Cadogan et al., 2010: Lum, Haff, & Barbosa, 2020). Additionally, the data collected from the isometric strength measurements can be used to estimate dynamic strength via regression equations (McDonald et al., 2018).

1.2. Strength estimation using Digital Human Models

Digital human models (DHMs) are virtual avatars that have developed to represent the shape, biomechanics and behaviour of humans. The assessment of work-related overexertion injuries can be examined using DHMs as it allows for the replication of postures most commonly used in physically demanding jobs at the workplace (Zhang & Chaffin, 2005). Ergonomists use DHMs to analyze postures, joint forces, and neuromuscular fatigue development under occupational conditions (Chaffin, 2005). Up until recently, DHMs used an approach that compared the static joint moment demand to population estimates of static joint strength. Within this approach, a rigid linked-segment model is used to estimate what reaction moments are required about the shoulder, elbow, and wrist, to maintain static equilibrium against an applied force and the weight of the arm itself. These results are then compared to the 75% of the female working population's strength values at the postures adopted with the linked-segment model (La Delfa et al., 2019).

Although this approach was widely used in the field of ergonomics within several popular DHM software platforms (e.g. 3DSSPP, University of Michigan, USA), recent research has uncovered many limitations (Hall, La Delfa, Loma, & Potvin, 2021, Hodder et al., 2016). In many ergonomics assessments, a primary outcome of these analyses is to determine the acceptable manual force that can be safely applied by the hands. These acceptable loads have been determined by studies evaluating Manual Arm Strength (MAS), or the maximum forces that can be generated by the arm with the hand as the end effector or point of force application. Ergonomists often refer to population estimates of MAS to determine the acceptability of applied manual forces.

1.2.1. Independent Joint Axis Static Strength Approach

The independent joint axis static strength (IJASS) approach is a static force optimization method used by some DHMs to compare the strength values of the population about each joint axis. The comparison is normally estimated for the 75% capable female working which is roughly equivalent to 99% of male workers (Chaing, Stephens, & Potvin, 2006). However, when it comes to the validation of MAS estimations, the IJASS method may be susceptible to many limitations. A primary limitation is that this method uses strength capability data that is nearly 40 years old (e.g. Stobbe, 1982), and therefore less representative of the current workforce. Another limitation is the accumulation of prediction errors across seven joint axis degrees of freedom, which are all required to estimate a single MAS value using this approach. Each individual joint strength prediction already has its own set of errors, thus the product of these errors accumulates on the total predicted force. In addition, strength data that looks at the force vectors passing straight through the joint results in strength capabilities that are very high (Fewster & Potvin, 2015). Hodder et al. (2016) showed that the IJASS approach misrepresents shoulder strength when exertions are required involving multiple degrees of freedom. Very recently, a comprehensive examination of the IJASS approach was conducted by comparing measured female linear arm strength against participant specific models created in 3DSSPP software (Hall et al., 2021). In this analysis, the IJASS approach was given every chance to succeed, as the joint strength of each participant was specifically programmed into 3DSSPP before using the IJASS to determine manual arm strength. The results showed that the estimated arm strength values were high (RMS error = 56.0 N and 40.4%) and poorly correlated (r^2 = 29.2%), compared to the experimental strength values. This study displayed the ineffectiveness of DHM software packages when estimated female linear arm strengths.

1.2.2. Arm Force Field

In light of the limitations noted in the traditional IJASS method, there was a need to develop an approach to more accurately estimate population strength for manual exertions. Initially, La Delfa et al., (2014) approached this problem by measuring and estimating strength capabilities directly at the hand; thereby eliminating the need to account for joint strengths across the entire upper limb. This approach evaluated manual arm strength in different anatomical force directions (i.e. anterior, posterior, superior, inferior, medial, and lateral) and several hand locations relative to the shoulder and produced predictive regression equations with hand location as the only inputs (La Delfa et al., 2014). Six equations were developed – one for each of the primary directions – all relative to an upright torso parallel to gravity, which is not indicative of all workplaces. Thus, the next iteration in this research resulted in the development of an Arm Force Field (AFF) method. The AFF predicts strength capabilities for forces applied by the hands in 75% females for any direction, hand location and torso orientation (La Delfa & Potvin, 2017). This approach circumvents many limitations that have been associated with predicting MAS in ergonomics. The AFF method is also able to determine MAS in any torso orientation by accounting for the weight of the arm in all strength estimations.

2. Factors Affecting Manual Strength

Strength refers to the ability to generate or withstand a substantial amount of force generated by a group of muscles (Mital & Kumar, 1998). There are several factors that play a role in the extent of force that can be exerted as the muscle is a complex organ which consists of skeletal muscle tissue, connective tissue, nerve tissue and blood or vascular tissue (Roy et al., 2009). Specifically referring to manual arm strength, there are two main types of factors that contribute to change in the amount of force exerted by the upper limb. The first are biomechanical factors, which refer to aspects of direction, location, balance, and surface friction, that can mechanically influence force production. A second set of factors that can influence manual strength are related to variability in the population. Population-based factors include demographic and anthropometric considerations such as age, sex, and handedness.

2.1. Task/Biomechanical Factors

2.1.1. Direction

Manual arm strength refers to the maximum force that can be exerted in any given direction by the arm with the hand as the end effector (La Delfa et al., 2015), and can vary significantly depending on direction of exertion and location of the hand relative to the shoulder (De Castro et al., 2012; La Delfa et al., 2014). Upper limb force production is greater when exerting force towards the midline of body from anatomical position as opposed to away from the midline of a body. A study that predicted manual arm strength on 26 possible force direction noticed the highest MAS value was in the posterior direction referring to when the hand is in front of the sternum relative to the shoulder with a moment arm of approximately 10 cm (La Delfa & Potvin, 2016). The lowest MAS value occurred when the arm was to the side and the hand by waist height with a moment arm of approximately 30 cm. In addition, exerting at an above-shoulder level height direction had a great influence on shoulder strength (Chow & Dickerson, 2009). Thus, individuals are stronger when force is more in line with the arm and when moment arm between hand and shoulder is minimized.

2.1.2. Hand Location

Different hand locations alter the force exerted by each muscle due to changes in the muscle's length-tension relationship. This is the consideration that single muscle fibers are unable to produce the same level of isometric force when positioned at different lengths (Harris & Warshaw, 1991, Ryan et al., 2010). Each muscle fiber has a resting length and the maximal generated force occurs close to the resting fiber length due to the sarcomere being the longest while at rest. Functionally, manual strength output tends to be maximized when, the location of the hand is mechanically advantageous to major muscle groups of the torso (e.g. pectoralis and latissimus muscles) (La Delfa & Potvin, 2016). Furthermore, Garg & Kapellusch (2005) conducted isometric shoulder strength testing at six different arm postures with maximal forces measured at zero degrees' shoulder flexion and 90 degrees' elbow flexion (Garg Hegmann, & Kapellusch, 2005). The arm posture that exhibited the lowest forces was 90 degrees' shoulder flexion and 120 degrees' elbow flexion. Thus, indicating the higher values accompany the optimal position when the muscle length is at its greatest mechanical advantage.

2.1.3. Balance & Foot Floor Friction

The strength exerted by the upper limbs is also dependent on the stability of the whole body. To efficiently perform workplace tasks, postural stability is a key factor as it refers to the static moment where equilibrium is met (Fischer et al., 2013). Associating the body with a lever system, the hand force and the force of gravity act as the center of mass where the area of the shoe-floor interaction is the point of the fulcrum. Thus, the location of the foot in reference to the hand location contributes the maximum applied force that can be exerted by the hand. In addition, a shoe-floor interface with less friction will result in low force level due to the instability of the body. Whereas, if the individual had a strong hold onto the floor surface without any risk of movement, the maximal manual arm strength output will be higher (Li & Lin, 2013). A study analyzing hand-force exertions during standing postures have noticed individuals tend to increase the distance of their pelvis and shoe-floor interface when exerting more maximal force (Hoffman, 2008).

2.1.4. Fatigue

As with all muscular exertions, prolonged and/or repetitive manual force production can be reduced via neuromuscular fatigue (Gandevia, 2001). The progression of neuromuscular fatigue leads to the inability to maintain a high degree of force (Enoka & Duchateau, 2008). The changes in force production could be either due to the individual's decrease in peripheral motor efferent viability and recruitment, or due to their decreased central drive. The result of neuromuscular fatigue leads to a decrease in motor unit firing rates as a signal is received by the brain to reduce central drive, resulting in a decline in force production (Gardiner, 2011). Peripheral fatigue also results in the decrease of force output either due to damage to the muscle fiber or the accumulation of metabolic waste (Kent-Braun, 1999). Other factors which can result in fatigue is lack of motivation, absent diet, and lack of sleep (Kent, 1999; Enoka & Duchateau, 2016). Therefore, it is important to control for all these transient factors during studies measuring maximum force production, or strength.

2.2. Population-Based Factors

2.2.1. Sex

Age and gender are also factors that affect strength measures, which is the reason why many studies account for both and mention their target population when determining a strength criterion (Hughes, Johnson, Driscoll, & An, 1999; Lopes et al., 2018; Roy et al., 2009). Males are generally stronger than females due to anthropometrics and muscle characteristics, which improve their mechanical advantage and muscular recruitment (Lopes et al., 2018; Roy et al., 2009). Current literature estimates that an average women’s strength is approximately two-thirds of an average man’s (Rasch, 1990). One study compared the maximal forces of pushing, lifting, hand grip and torque of pronation and supination actions among males and females 20 to 31 years of age (Roman-Liu & Tokarski, 2005). Higher force values were observed in the male population 21 to 31 years of age compared to age matched females. The general consensus is that as age increases, strength decreases. Muscle fibre size tend to decrease with age thus, causing atrophy of the muscles. (Deschenes, 2004; Thompson, 2009). A longitudinal study looked at 3075 individuals, male (48%) and female (52%), aged 70-79 years (Goodpaster at el., 2006). After 3 years of assessing strength, both men and women were at a loss. Males lost roughly 4% of their muscle mass and females lost 3%. Although loss in muscle mass could also be due to sedentary behaviour, strength decline due to age is much more rapid suggesting a decline in muscle quality. Therefore, changes in age and gender have shown to be present with significant differences in strength.

2.2.2 Anatomy

Despite the apparent visual symmetry of the upper limbs, the right and left arms have notable anatomical differences. Bilateral differences in upper limb anatomy have been noted even before birth. In 1971, Pande and Singh examined the upper limb muscles and bones of 10 fetuses pre-term. The results indicated that the right limb showed greater muscle and bone weight, a difference of roughly 5% heavier. Indicating that 9 out of 10 individuals' total muscle and bone weight was greater for the right limb, which is consistent with the right-to-left handers in the general population (Moscovitch, 1976; Gutnik & Hyland, 1990). A study that examined the length of the humerus in 623 fetuses displayed that roughly 50% or more of the cases the right humerus was longer. (Shultz, 1926). The general consensus is that the right arm and forearm seem to be longer and display a greater circumference, as it is the more frequently used arm in daily activities (Krzykala & Leszczynski, 2015: Salazar-Preciado, 2021). There is minimal research on left-handed individuals and the anatomical bilateral differences of the upper limb, but this could be due to the lack of left-handed people in the population. A study looked into the bilateral differences from 605 children ages 6-12 years, 93% of which were right hand dominant (Salazar-Preciado, 2021). The results indicated significant differences in the triceps skinfold and mid-upper arm circumference with r values of .99 and .98. These anatomical differences can be a factor to the strength asymmetry noticed between the arms.

2.2.3. Handedness

The term ‘handedness’ designates which limb is more favoured by an individual during day to day tasks. The preference of using one limb over the other when performing tasks has made the dominant limb more skilled, demonstrating greater speed, strength, and dexterity (Demura, Miyaguchi, & Aoki, 2010). Thus, muscles on the dominant side become more accustomed to regular recruitment, resulting in potential functional performance improvements in strength (Arora, Budden, Byrne, & Behm, 2015). Demura, Miyaguchi and Aoki (2010) analyzed the differences in strength output from the dominant and non-dominant limb, through isometric, isokinetic, and isotonic muscle power tests. All participants were right-handed males performing elbow flexion with both of their arms. Significant differences were noticed between dominant and non-dominant limbs in the isometric (D:ND = 55:45) and the isotonic (54.1:45.9) tests, but not in the isokinetic test (60°s^{-1}, 51.4:45.9). Interestingly, the dominant (right) limb expressed greater strength in isometric and isotonic tests compared to isokinetic tests. Accessing muscle function of the dominant limb compared with the non-dominant during isokinetic strength tests is fairly difficult due to the special conditions that accompany isokinetic testing which can possible affect the subjects’ skill, experience, and motivation (Demura et al., 2010). The current generally applied assumption is that the non-dominant limb is approximately 90-95%% strength of the dominant hand, however there is little evidence supporting the validity of the assumption (Demura et al., 2010; Van Harlinger, Blalock, Merritt, 2015).

3. Limb Dominance

3.1. Neurophysiological Bases for Limb Dominance & Handedness

The brain consists of two hemispheres, the left and right. With regards to motor lateralization, studies have suggested that for left-hemispheric individuals (right hand dominant), their right hands perform with predicative, feedforward control and movement planning. Whereas, the individuals who are right hemisphere dominant (left hand dominant) perform with feedback-mediated error correction mechanisms (Magill & Anderson, 2014). This means that right hemispheric dominant individuals show evidence of relying on sensory cues to change their output when completing a task (Shabbott & Sainburg, 2008). These factors largely influence an individual's hand preference. Limb dominance, however, develops later (between the ages of 4-6), when the individual has peaked in their motor development. The motor system is involved in planning, controlling and the execution of voluntary movements (Magill & Anderson, 2014). It involves upper motor neurons which are responsible for delivering signals to interneurons and the lower motor neurons, during the initiation of movement. The lower motor neurons transmit the signal directly to skeletal muscles which produce force and cause movement.

The upper limbs are essential parts of the body during infancy, learning about objects and their parts whiles transporting the objects to different places (Nelson, et al., 2017). The coordination between the hemispheres is how infants learn how to use the hands together. However, the theory of handedness is thought to begin in infancy through a sequence of environmental interactions and the greater use of one hand over the other (Coryell & Michel, 1978). All developing infants will experience reaching and maneuvering skills, but the pattern at which hand they use across varying manual skills differs. Handedness is thought to be a reflection of hemispheric specialization or asymmetric brain function, though the control of manual actions has been shown to be driven by experience (Nelson et al., 2017). Predominantly, the limb that is utilized the most performs better in manual exertions due to the fact that the muscles have become accustomed to adapt greater tolerance (Fischman, 2009). This enhances the control and dexterity of motor recruitment for larger muscle fibers in the preferred limb.

The large muscles of the upper limbs are the main contributors to the strength differences noticed between the limbs. These muscles consist of biceps brachii, brachioradialis, deltoids and triceps brachii. Skeletal muscle is made up of muscle fibers running parallel to the length of the muscle (Beale, 1859; Jacobson & Marcus, 2011). Therefore, the transmission of force from the muscle fibers to the intermuscular connective tissue has shown to be affected by the stiffness of the skeletal muscle (Magill & Anderson, 2014). Stiffness is developed by the lack of movement or usage. Thus, when one prefers the use of their right hand in most activities, the muscles on the left hand will start to stiffen, creating a performance insufficiency on one limb

(Jacobson & Marcus, 2011). Though handedness cannot be attributed to any one factor, it is apparent that the origins and maintenance of handedness are due to a combination of neurophysiological, anatomical and biomechanical factors that start in our infancy and strengthen over time.

3.2. Performance Differences Between Limbs

3.2.1. Upper vs Lower Extremities

The upper and lower extremities are both separated into three segments with each segment having roughly the same bone framework starting with a single bone at the most proximal point, two bones at the middle segment, and carpals/tarsals, metacarpals/metatarsals, and phalanges at the most distal segment (An & Chao, 1984). Despite this similar framework, the upper and lower limbs are very different in mobility, as the upper limbs are less firmly attached to the thorax and are therefore more mobile (Kinzel, Hall, & Hillberry, 1972). The upper limbs also function for grasping and movement whereas, the lower limbs functions more for weight bearing and locomotion. Thus, the upper limbs yield a greater relative strength increase during training responding with greater muscular adaption (Sousa & Sampaio, 2005). Increased strength in the lower limbs can lead to a better sense of proprioception and postural control (Sousa at al., 2011). Age tends to affect the lower limbs more due to the reduction in physical activity (Candow & Chilibeck, 2005). This leads to the reliance of the upper limbs to help with movements such as getting up from a chair or climbing up/down the stairs. However, as mobility is dependent on the active usage of the limb, the muscles of the lower limbs may be more active throughout one's lifetime which would result in less strength losses.

3.2.2. Motor Control/Accuracy

Motor control is measured by the motor cortex selectively exciting motor units to contract muscles in synergy and initiate a voluntary movement (Magill & Anderson, 2014). Thus, due to the hemispheric specialization of hand preference, the initiation of movements between both upper limbs present with some differences (Murtha et al., 2013). The current assumption is that one arm is more specialized in all aspects of motor control while the non-dominant arm is weaker in all aspects. However, there are many complex behaviors associated with motor laterization which establish different strengths between each arm. The dominant arm has an advantage when it comes to speed responding to visual and proprioceptive feedback more quickly (Roy, 1983; Carson et al., 1990; Elloitt et al., 1995). However, the non-dominant arm is proposed to have better feedforward control and movement planning. The non-dominant arm also often displays better accuracy and precision in proprioception (Bagesterio & Sainburg, 2003). The hypothesis is that the dominant arm's motor system is enhanced in performing dynamic movements in relation to its direction and trajectory (Sainburg, 2002; Schaefer, Haaland, & Sainburg 2009). Whereas the non-dominant arm's motor system specializes in attaining postures that are stable through equilibrium (Wang & Sainburg, 2007).

3.2.3. Strength

3.2.3.1. Individual Joint Strength

Many daily tasks are dependent on upper limb strength. When it comes to the estimation of upper limb strength in ergonomics, only three major joints are largely considered: the wrist, elbow, and shoulder. The shoulder complex has the largest range of motion and utilizes a complex interaction of musculature to control movement. In baseball pitchers, the glenohumeral joint of the dominant upper limb presents with more strength, causing an imbalance which, if not maintained, can lead to glenohumeral joint disorder (Lyman et al., 2001). The strength differences between the dominant and non-dominant upper limb are largely due to the contribution of the shoulder and the overall differences are the result of impaired function in one of the two limbs (Noguchi et al., 2014). However, outside of athletes that play unilateral sports, the differences in strength at the shoulder joint are minimal. The elbow joint is classically defined as a hinge that has two primary exertion directions: flexion and extension. The maximal elbow strength at flexion-extension occur when the elbow is flexed at 90 degrees' (Singh & Karpovich, 1968). When examining the strength differences between the elbow joint there were no significant bilateral differences in the strength measurements (Newton et al., 2013; Noguchi et al., 2014). Interestingly, evidence of crossover is present when strengthening one side of the upper limb, approximately 10 percent of the strength increase is noticed on the other side, suggesting some cross-hemispheric neural adaptation with strength training.

3.2.3.2. Manual Exertions

There is a definite assumption, across ergonomics and other clinical realms, that the dominant arm is stronger than the non-dominant arm (Crosby et al., 1994; Armstrong & Oldham, 1999; Farthing et al., 2005; Malshikare et al., 2019). There are many advantages in the preferred limb that facilitate the generation of increased motor output. On average, the dominant upper limb has roughly a 10% higher force output than the non-dominant arm (Armstrong & Oldham, 1999; Malshikare et al., 2019). This is due to the increased use of the dominant upper limb compared to the non-dominant for majority of motor tasks. In addition, the combined force generated by the individual limbs unilaterally has shown to be higher than the force generated by the same muscles when contracting both limbs simultaneously (Howard & Enoka, 1991; Koh et al., 1993; Jakobi & Chilibeck, 2001; Simoneau-Buessinger et al., 2015). This phenomenon is referred to as the bilateral strength deficit. In 1901, Henry and Smith reported a 3% significant deficit in force output from the dominant limb during bilateral contractions compared to unilateral contractions.

An isokinetic manual exertion study was done on professional tennis players comparing laterality. The results indicated an overall greater manual strength in the dominant arm compared to non-dominant (Ellenbecker, 1991). However, tennis is a highly unilateral sport where the athlete mainly uses their dominant limb over the other. Overall, the preferred upper limb presents with 10-15% higher strength output values compared to the non-preferred limb (Yielder, et al., 2009). Though, the non-dominant limb demonstrates various behaviors to further assist in accuracy and proprioception while exerting force (Ellenbecker, 1991). Much more research is needed to determine how strength differs between limbs in the general working population, where sport-task driven differences are less likely to be driving the discrepancy between strength.

3.2.3.3. Strength Asymmetry: The 10% Rule

The force generated within the muscle is dependent on the length of the muscle, the relative position and the contribution of the quantity and type of muscle fiber types (Roy et al., 2009). These factors in relation to the upper limbs influence and contribute toward asymmetry and handedness (Yielder et al., 2009). The difference in strength symmetry between limbs has often been described according to a “10% rule”. However, there are two utilizations of this rule - both of which provide evidence of the asymmetry that exists in the upper limbs. The first interpretation states that the dominant hand is approximately 10 percent stronger than the non-dominant hand. This is more of an average value, with the research ranging from a 3-22.6 percent range in reported discrepancy in dominant to non-dominant strength asymmetry (Yielder et al., 2009, Bohannon, 2003, Gutnik & Hyland, 1990, Armstrong & Oldham, 1999). Another utilization of the 10 percent rule is that 1 out of 10 individuals, or 10% of subjects, have equal or higher strength in their non-dominant hand. This has historically been observed in right-handed individuals, but lefties do not seem to show the same degree of asymmetry. In fact, left-handers often show very balanced strength between their limbs. It is likely that this balanced strength is a consequence of left-handers being forced to use their non-dominant hand more frequently in right-hand centric world.

4. Conclusion: Gaps in Research

Strength is a universal indicator of one's overall health and physical capabilities (Bohannon, 2015). Measuring strength is a common method used in many studies looking at its effects on performance, metabolism, and body weight but also its management in reducing any risk of health complications, disease, and injury. In the field of ergonomics, strength has been used to guide safe workplace designs and optimizing efficiency while also lowering the risk of injury. Ergonomists set limits so the strength demands of a workplace do not exceed the strength capabilities of approximately 75% of the population (Waters et al., 1993). As such, manual arm strength data is often sought by ergonomists and design engineers to design acceptable work tasks, but many of these data points were derived from one-handed strength measures from the dominant limb of right-handers. This is not indicative of many occupational scenarios where the non-dominant limb is involved in the task as well. Therefore, there is a gap in the literature with respect to the manual arm strength differences in both limbs. Further studies are certainly needed in this area to contribute to our existing capabilities in estimating acceptable force limits.

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Chapter 3.

Examining Differences in Manual Arm Strength Between Dominant and Non-Dominant Limbs

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1. Introduction

Many occupations involve the utilization of the upper limbs. These work-related tasks require precise effort with the hands (e.g. office computer work), or utilize the entire arm for force and torque exertion (e.g. factory workplaces) (Garg & Kapellusch, 2012). Common workplace tasks often require the arm to be held in uncomfortable and awkward positions, which can decrease upper limb strength and leave workers more susceptible to musculoskeletal injuries (Nimbarte et al., 2012). A vast amount of research has analyzed WMSDs and their association with risk factors regarding upper extremity tasks (Grayson et al., 2005; Hossain et al., 2018; Punnett et al., 2004). Most lost-time injury claims in the workplace are sprains, strains and other soft tissue injuries (WSIB, 2018). In 2018, approximately 21,600 cases were reported for over exertions injuries to the upper extremities (WSIB, 2019). Thus, a major focus in ergonomics is to identify the main mechanisms related to work-related injury, including reduction of excessive force demands.

An important facet of occupational design involves the estimation of human strength capability to ensure the force and moment demands of the job do need exceed capacity limits of the worker. Previous research has proposed acceptable force demands for common work-related tasks, including lifting, lowering, pushing, pulling and carrying (Ciriello & Snook, 1999; Ciriello, Snook, Hashemi, & Cotnam, 1999; Mital & Kumar, 1998; Potvin, Chiang, McKean, & Stephens, 2000; Garg et al., 2012). To estimate acceptable manual loads for more unique tasks and postural configurations, digital human models (DHMs) can be implemented, especially when tasks need to be assessed proactively (Chaffin, 2005). In these biomechanical analyses, if a manual force requires a joint strength demand that exceeds the capacity of any segments within the kinetic chain (i.e. the shoulder, elbow or wrist), then the task is deemed to be unacceptable. Despite this being a standard approach in many software packages, the assumption that manual strength can be estimated in a 'weakest link' type approach has resulted in very high errors in comparison to empirical measurement of manual arm strength (MAS) (Hall et al., 2021).

As an alternative, predicting strength capability of the entire arm can be useful in optimizing work tasks within ergonomics limits (La Delfa et al., 2014). La Delfa et al. (2014) initially produced equations to estimate MAS for single force directions, and later optimized these MAS predictions using an artificial neural network for more robust predictions across any force direction, hand location and torso posture (La Delfa & Potvin, 2017). This Arm Force Field method is now implemented as an alternative approach to estimate strength within DHMs. However, in all approaches used to estimate acceptable force demands, there is a noticeable gap in the consideration of hand dominance, especially considering forces are often applied by both hands in industrial tasks.

The origin of handedness is often attributed to the lateralization of the brain into two primary hemispheres (Yielder et al., 2009). It is argued that individuals who are right-handed use the left hemisphere more often and individuals who are left-handed tend to use their right hemisphere more often (Magill & Anderson, 2014). Handedness is defined as the preference of using one hand over the other. Handedness is intimately related to the idea of limb dominance, which refers to one limb being more skilled and demonstrating greater speed, strength, and dexterity in comparison to the other limb due to its more regular use (Demura, Miyaguchi, & Aoki, 2010). Aside from neurophysiological origins, there are several biomechanical explanations also offered to describe this strength discrepancy between limbs. Strength differences between the dominant and non-dominant limbs are dependent on the contractile units of the muscle fibers that connect the muscle membrane through a variety of proteins (Magill & Anderson, 2014). The perimysium, which is the layer that surrounds the bundles of muscle fibers, affect the stiffness of the muscle. Therefore, the transmission of force from the muscle fibers to the intermuscular connective tissue has shown to be affected by the stiffness of the skeletal muscle. As such, the explanation for limb dominance and handedness is complex, with links to anatomical, biomechanical and neurophysiological factors.

The current assumption, made by several ergonomic software packages, is that the non-dominant limb has approximately 90-92.5% the strength of the dominant limb (e.g. 3DSSPP); however, there is little evidence supporting the validity of this assumption (Demura, Miyaguchi, & Aoki, 2010; Van Harlinger, Blalock, Merritt, 2015). Much of the strength research currently used to estimate acceptable force limits were derived from one-handed strength measures from the dominant limb (e.g. Stobbe, 1982; La Delfa, 2014, 2016). However, this is not representative of many occupational scenarios where the non-dominant limb is involved in the task as well.

There is also a phenomenon that is referred to as the 10 percent rule. This refers to 10% of subjects having equal or higher strength than their non-dominant arm (Yielder et al., 2009), and also represents an approximate average discrepancy between dominant and non-dominant limb strength. However, these relationships have been observed on primarily right-handed individuals (Lanshammar & Ribom, 2010;Cortez et al., 2011; Noguchi et al. 2014). As such, incorporation of left-handed individuals within these assessments is vital to better represent the strength of the population. Furthermore, if discrepancies between right- and left-handers are understood, better design decisions could be made to accommodate the 10-13% of the population that considers themselves left-handed (McCarthy & Richter, 2020).

The main objective of this study was to determine the difference in manual arm strength between the upper limbs when performing maximum exertions in several hand locations and force directions. We hypothesized that the dominant limb will yield greater strength values than the non-dominant limb. Additionally, the difference in dominant and non-dominant strength will vary significantly between the different hand locations and force directions. We also hypothesized that right handed individuals will have a greater strength discrepancy between their dominant and non-dominant upper limbs compared to left-handed individuals (Petersen et al., 1989; Armstrong & Oldham, 1999; Nicolay & Walker, 2005).

2. Methods

2.1 Participants

Twenty-six healthy participants (13 M and 13 F) between the ages of 18-30 were recruited from the Ontario Tech University's student population. Handedness was determined via the Edinburgh handedness inventory which utilizes 10 items to assess hand preference for everyday tasks (Oldfield, 1971). An equal number of right-dominant and left-dominant participants were recruited. Exclusion criteria included any acute or chronic upper extremity pain, injury, or surgery within one year prior to the data collection. Two additional participants were deemed ambidextrous and not included in the analysis. All participants provided written and verbal consent before their participation in the study.

Table 1: Participant demographics separated by handedness and sex. Handedness score evaluated by -100 (pure left), -50 (mixed left), 0 (neutral), 50 (mixed right), 100 (pure right)

	Right-Handed [n=12]		**Left-Handed[n=12]**	
	Female [n=6]	**Male [n=6]**	**Female [n=6]**	**Male [n=6]**
Height	*166.67 ± 5.84*	*180.33 ± 5.33*	*159.64 ± 6.23*	*176.83 ± 6.25*
Weight	*64.32 ± 9.41*	*78.04 ± 13.64*	*65.78 ± 14.11*	*71.05 ± 13.02*
Age	*21.33 ± 0.82*	*21.67 ± 2.58*	*19.86 ± 1.57*	*24.33 ± 6.05*
Handedness score	*82.75 ± 17.16*	*71.60 ± 12.61*	*-68.33 ± 17.71*	*-80.47 ± 19.15*

2.2 Instrumentation

2.2.1 Dynamometry

Manual forces were measured using a vertically-orientated handle mounted to a 6 degree-of-freedom transducer (PY6-500, Bertec Corporation, Columbus, OH, USA). Participants were seated and restrained in a solid chair, fastened to a thick piece of plywood, isolating strength production to the arm and minimize contributions from the legs and torso (LaDelfa & Potvin, 2017). The handle-transducer assembly was mounted to a height adjustable wall mount, and the participants' lateral and horizontal distance relative to the handle were manipulated by moving the chair. Data were sampled at 1000 Hz and visual online force feedback was provided to aid in the force exertions (Figure 1).

2.2.2 Kinematics

Upper extremity kinematics were measured using three banks of OptoTrak 3D Investigator cameras (Northern Digital Inc., Waterloo, ON, Canada) at a sampling rate of 50 Hz. Four sets of at least three infrared emitting diodes were affixed to plastic rigid bodies and secured to the dorsum of the hands, forearm, and upper arms of both limbs, as well as the back of the thorax. Several landmarks of the torso and upper extremity were digitized and virtually tracked relative to the fixed rigid bodies. Kinematics were collected according to the ISB recommendations (Wu et al., 2005). The kinematics and force data were time synchronized via trigger signal sent from the data acquisitions system to the Optotrak cameras.

2.3 Protocol

Participants conducted exertions at 3 hand locations: 1) Umbilicus height at 45° in the plane of elevation (i.e. rotated laterally 45° relative to sagittal plane), 2) Shoulder height at 0° (i.e. arm flexed to shoulder height) and 3) Overhead height at 45° in the plane of elevation. Arm reach was set to 80% of maximum reach, measured from acromion to the 2nd metacarpophalangeal joint. These parameters define the hand locations that were mirrored for the right and left hands. The above procedures are in accordance with prior work (La Delfa & Potvin, 2016) and were strategically chosen to create conditions with minimal shoulder moment arm (i.e. push/pull at shoulder height), as well as conditions requiring a complex upper extremity joint moment profile to achieve the task (i.e. both 45° locations). Order of hand locations were block-randomized, with conditions cycling between right and left arms, to further build in rest periods for each involved muscle group. MAS was measured in 6 unique exertions directions: push (anterior), pull (posterior), up (superior), down (inferior), right and left (medial or lateral, depending on hand of exertion). All 6 exertions were completed in a randomized order. Therefore, a total of 3 hand location x 6 exertions x 2 hands = 36 MAS trials were conducted. Previous research included up to 54 MAS exertions in one arm in a given test day, with no evidence of muscle fatigue affecting MAS readings (La Delfa & Potvin, 2016).

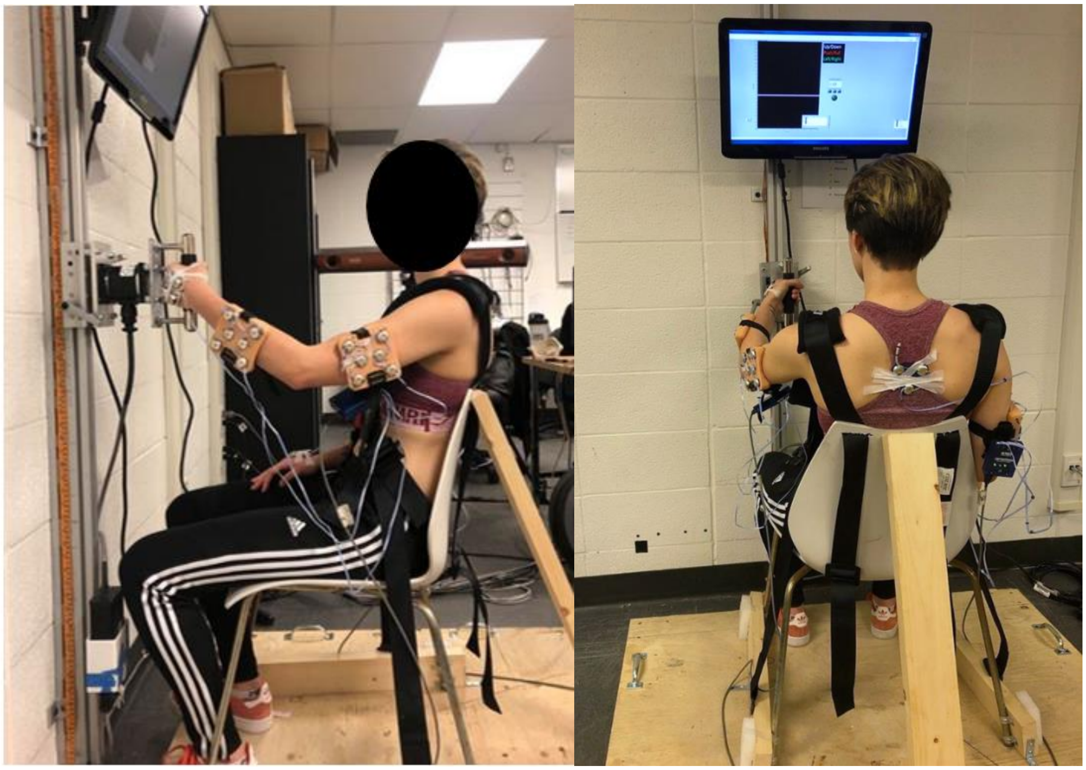


Figure 1. Experimental set-up. Participant strapped in at shoulder hand location and seated in front of a monitor with visual feedback.

Participants ramped up their force production over 2-3 seconds to stabilize their force direction, using online visual feedback displayed on a computer monitor, then held their maximum exertion for 2-3 seconds with consistent verbal encouragement provided by the experimenters. Participants then ramped down their force application in a controlled manner, again over a 2-3 second period. For all strength exertions, at least 1-minute of rest was provided between exertions, with no exertion repeated consecutively. At least 90% of the resultant force needed to be directed within the required direction for a trial to be considered valid. If this criterion was not met, the trial was re-collected at the end of the block of exertions.

2.4 Data Analysis

Dynamometry and kinematics signals were combined in an inverse dynamics approach to determine quasi-static upper extremity joint moments during all manual arm strength trials. Force signals were smoothed using a 1-second moving average and manual arm strength was taken to be the peak resultant force calculated from the tri-axial force outputs (La Delfa & Potvin, 2016). A rigid-linked segment model was created for each participant using approximations of their joint center locations, according to International Society Biomechanics (ISB) conventions (Wu et al., 2005). Segmental masses and center of mass locations were approximated using participant anthropometrics, and the tri-axial force signals were applied to the palm of the hand. Bi-lateral joint moments were computed about the shoulder (i.e. flexion/extension, humeral rotation, negative elevation), elbow (i.e. flexion/extension, pronation/supination) and wrist (i.e. flexion/extension, radial/ulnar deviation). The joint moment data were analyzed as the difference between the dominant joint moment and non-dominant joint moment values. Visual 3D software was used to compute joint angles using Euler decomposition sequences recommended by the ISB (Wu et al., 2005) and specific joint angles obtained at the time of the peak MAS were isolated. Joint angle data explored descriptively, but not compared between limbs for this evaluation.

2.5 Statistical Analysis

For the MAS trials, the dependent variables include MAS (N) and the corresponding D/ND joint moment differences (N.m) and joint angles (degrees) at the precise time MAS was achieved within the trial. MAS was evaluated using separate 4-way mixed-model repeated measures ANOVAs for each of the six exertion directions. In these models, dominant hand (2 levels: D vs ND) and hand location (3 levels: Ovrd, Shld, Umb) served as within variables and handedness (2 levels: right-handed, left-handed) and sex (2 levels: male, female) served as between factors. Bonferroni adjustment was used to account for multiple tests ($p<0.0083$ required). A 4-way mixed model ANOVA was conducted for each joint to evaluate the effects of sex, handedness, exertion direction, and hand location and all potential interactions on shoulder, elbow and wrist moment differences. A Greenhouse-Geisser correction was applied to all within-subject's factors of each ANOVA to adjust for a lack of sphericity. For significant dependent variables ($p<0.05$), subsequent repeated measure ANOVA testing and Tukey HSD post hoc comparisons were conducted on significant ($p<0.05$) main effects and interactions.

3. Results

3.1 Manual Arm Strength

For MAS, there was a 3-way interaction between dominance, hand location, and handedness for the pull direction ($F_{(2,2)}=6.58$, $p=0.003$). For the left-handed individuals, their dominant hand was 23% stronger than the non-dominant at the umbilicus hand location (Figure 2). Similarly, the right-handed individuals had a 23% difference between dominant and non-dominant hands observed at the shoulder hand location only.

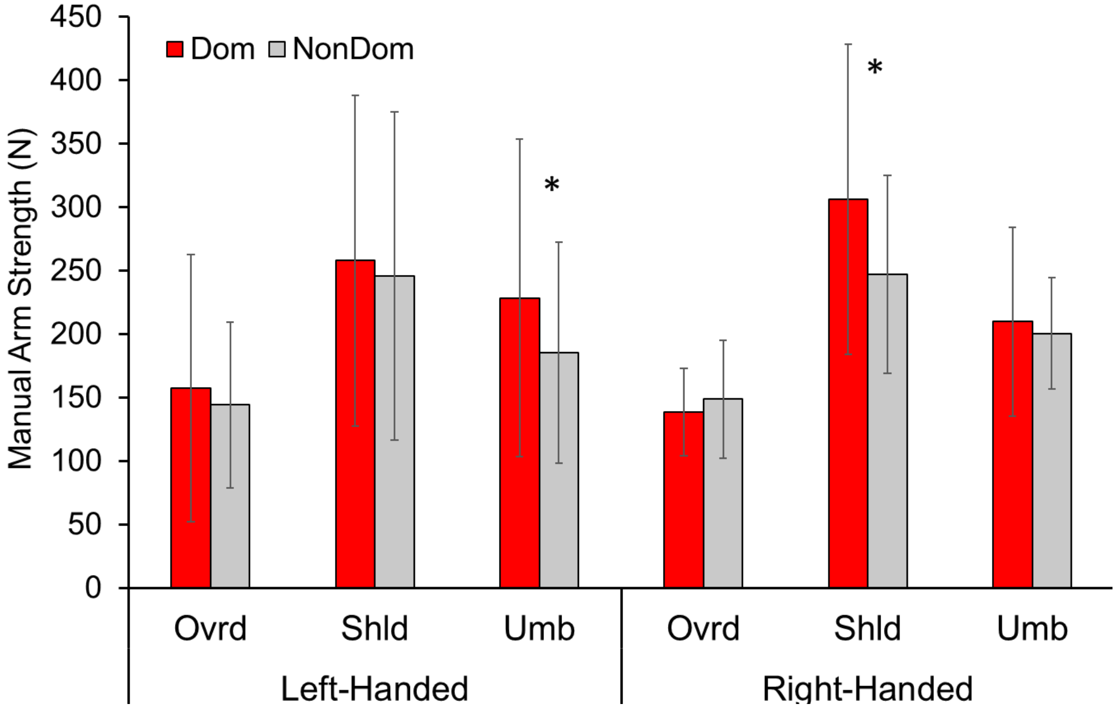


Figure 2: Manual arm strength for the pull direction for all 3 hand locations compared between hands. (*) indicates significant difference between the dominant (red) and non-dominant (grey) limb ($p<0.05$). Standard deviation bars are shown.

A 2-way interaction between dominance and handedness was found for the medial direction ($F_{(1,42)}=8.75$, $p=0.007$) There was a significant difference between arms for the right-handed individuals only, where the dominant limb was roughly 13% stronger than the non-dominant (Figure 3). Left-handed individuals had relatively balanced strength between dominant and non-dominant arms.

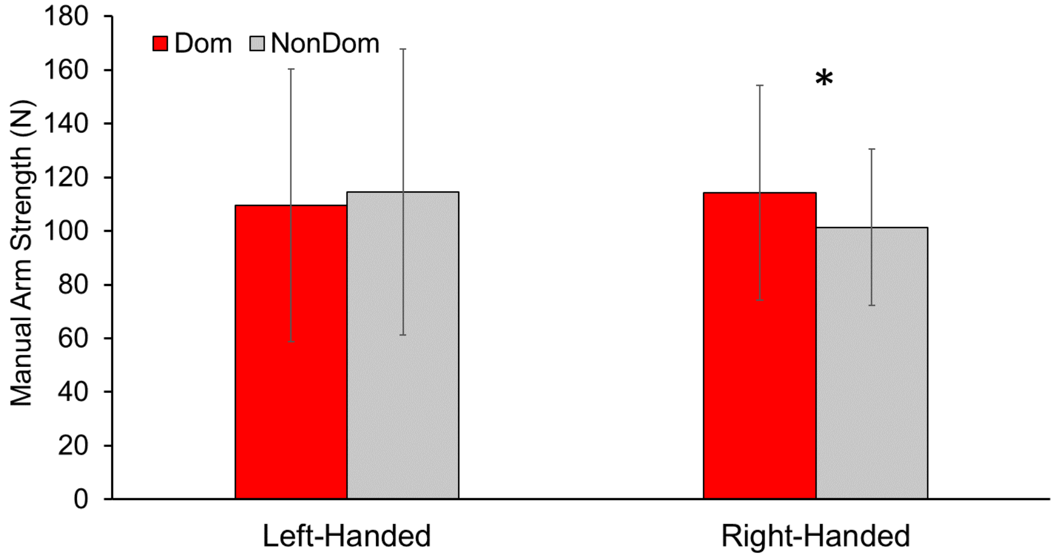


Figure 3: Medial direction manual arm strength data for left and right-handed individuals. (*) indicates significance between the dominant (red) and non-dominant (grey) limbs ($P<0.05$). Error bars indicate standard deviation.

Main effects of hand dominance also existed for the push ($F_{(1,21)}=11.43$, $p=0.003$) and pull ($F_{(1,21)}=10.48$, $p=0.004$) directions (Figure 4), and a main effect of hand location for all of the directions but lateral. For the push and pull directions, the dominant arm was 8% and 10% stronger than non-dominant arm, respectively. There was also a main effect of sex for all directions (Figure 5), with females having approximately 65.4% the strength of males across all exertion directions. Across all groups (left-handed, right-handed, and both sexes, the non-dominant hand was stronger in 41.1% of the conditions (Table 2). However, when broken down by handedness groups, left-handed individuals were stronger with their non-dominant right hand in nearly half (46.2%) of all trials, compared to only 35.6% for right-handers (Table 3). Minimal sex differences were observed for right-handers, but left-handed females were stronger with their non-dominant arm more often than they were for their dominant arm, but left-handed males tracked similarly with right-handed individuals. Accuracy of task exertion, represented by the % of resultant force in the required direction, remained consistent throughout the trial with an average of 96% accuracy in the intended direction between handedness, dominance, and sex (Table 4).

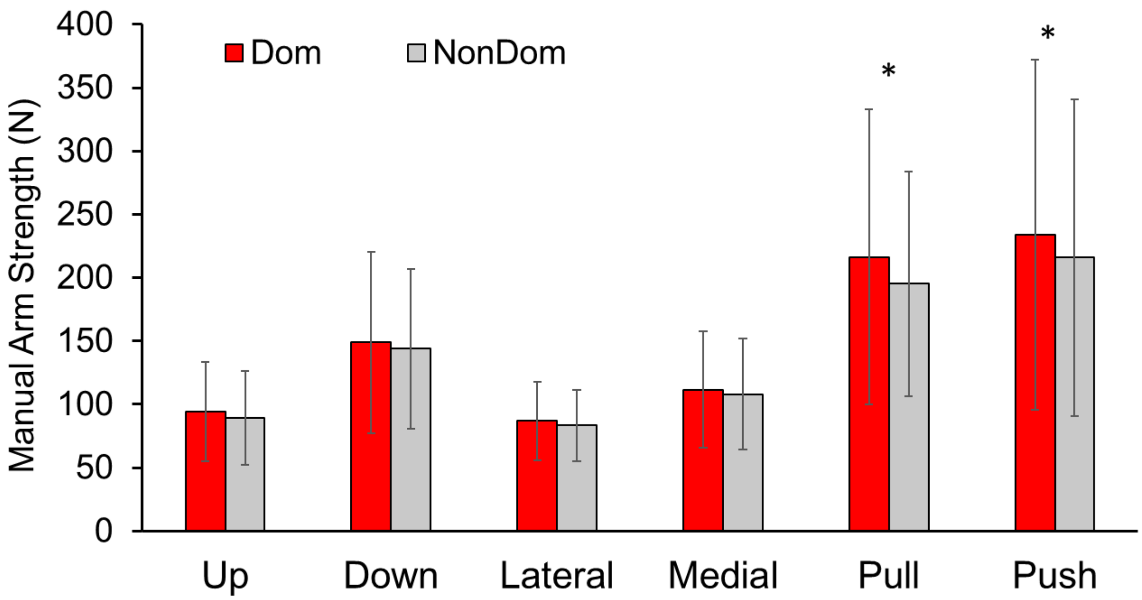


Figure 4: Manual arm strength at all 6 directions. Significance (*) of dominance noticed in the push and pull direction ($p<0.05$). Standard deviation bars are shown.

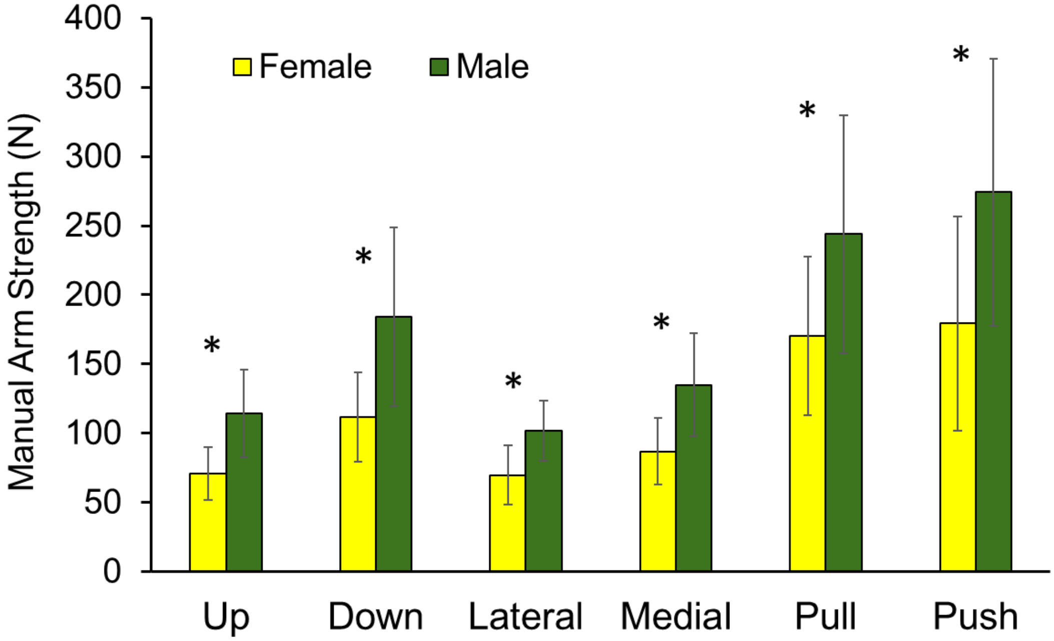


Figure 5**.** Manual arm strength data compared by sex was found to be significant (*) throughout all 6 directions. Standard deviation bars are shown

Table 2. F statistic and significant p=value summary table for all main effects of sex and direction.

Directions	F Statistic	p-value	Effect size
Up	*12.22*	*0.0004*	*0.455*
Down	*17.56*	*0.002*	*0.368*
Lateral	*12.97*	*0.002*	*0.382*
Medial	*15.23*	*0.001*	*0.420*
Pull	*6.25*	*0.021*	*0.229*
Push	*6.83*	*0.016*	*0.245*

Table 3. Percentage of conditions where the non-dominant hand was stronger, sub-divided by handedness and sex groups.

Handedness	Sex			
Left-Handed	Female	54.8%	46.2%	41.1%
	Male	36.1%		
Right-Handed	Female	35.2%	35.6%	
	Male	36.1%		

Table 4. Average percentage of resultant force, sub-divided by handedness, sex, and dominance

Handedness	Sex	Dominant	Non-Dominant
Left-Handed	Female	96.2%	96.3%
	Male	96.5%	96.3%
Right-Handed	Female	95.8%	95.8%
	Male	96.9%	96.4%

3.2 Joint Moments

3.2.1 Shoulder Moments

For the shoulder joint moments, two significant main effects were found for sex ($F_{(1,19)}$=5.57, p=0.029) and handedness ($F_{(1,19)}$=6.42, p=0.02) (Figure 6). The male individuals had greater shoulder moments in their dominant arm with a difference of 3.28Nm. Whereas for the females the shoulder moments were reasonably similar between hands having a difference of only 0.09 Nm. Likewise, the right-handed individuals had greater shoulder moments in their dominant hand, a difference of 3.49 Nm greater than their non-dominant hand. Left-handed individuals had shoulder moments greater on their non-dominant limb (shoulder difference of -0.87 Nm).

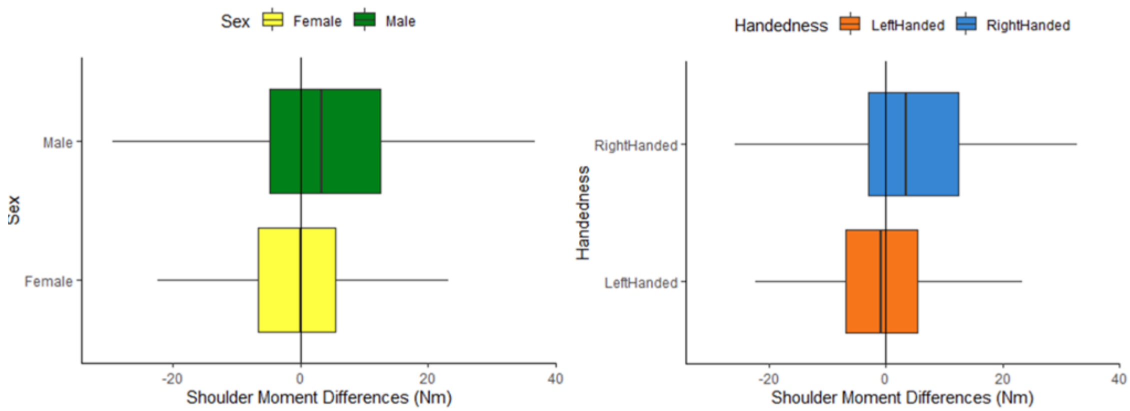


Figure 6: 2 box plot graphs showing shoulder moment differences (Nm) between males (green) and females (yellow) as well as between left-handed individual (orange) and right-handed individuals (blue). Median is shown by the middle line of the box followed by the upper quartile range (right side) and lower quartile range (left side).

3.2.2 Elbow Moments

For the elbow joint moments, we found a 2-way interaction between direction and handedness ($F_{(3,68)}$= 2.92, p=0.031) (Figure 7). The right-handed individuals had a significantly higher elbow moment in their dominant limb for the up and medial direction, when compared to the left-handed individuals. In the up direction, both left-handed and right-handed individuals obtained greater values on their dominant limb. The right-handed individuals had an elbow moment difference of 3.84 Nm in the up direction, and the left-handedness individuals had an elbow moment difference of 1.96 Nm in the up direction. In the medial direction, only the right-handed individuals had a greater elbow moment difference in their dominant hand (Elbow moment difference of 3.35 Nm). The left-handed individuals non-dominant elbow moment differences were slightly larger (elbow joint moment difference of -1.93 Nm), which was noticed in all the other directions.

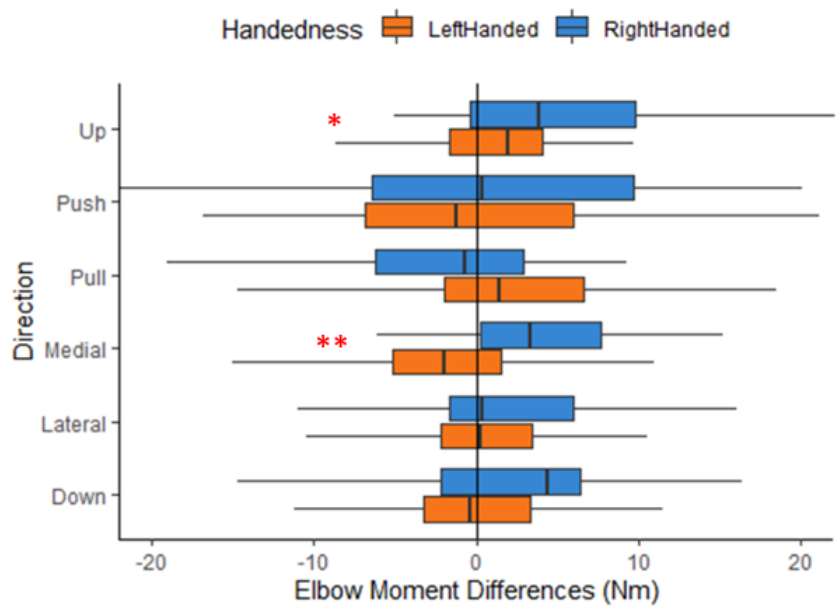


Figure 7. Elbow moment differences interaction in all 6 directions compared between hands. Significance (*) was noticed between hands in the up and medial direction (P<0.05).

3.2.3 Wrist Moments

The wrist moments showed 2-way interactions between handedness and direction ($F_{(2,54)}$= 17.192, p<0.0001) and handedness and location ($F_{(1,34)}$= 5.77, p<0.001) (Figure 8). The right-handed individuals had significantly higher wrist moment differences on their dominant hand in all directions, except for the pull direction (wrist moment difference of 4-6 Nm). Conversely, the left-handed individuals in all the significant directions had greater wrist moment differences on their non-dominant hand (wrist moment difference of -1 to 0 Nm). The interaction between handedness and location had the same pattern.

The right-handed individuals had greater wrist moments in their dominant hand for the umbilicus, shoulder, and overhead location (wrist moment difference of 5 Nm, 3 Nm, & 4 Nm). Whereas, the left-handed individuals had greater wrist moments in their non-dominant hand for all hand locations (average wrist moment difference of -1 Nm).

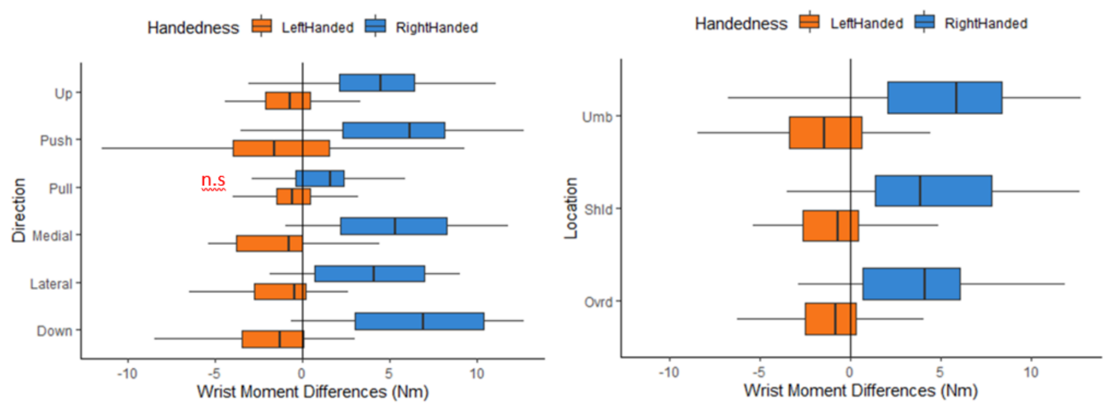


Figure 8. 2 box plot graphs comparing wrist joint moment differences between hands in all 6 directions and 3 hand locations separately. Only the pull direction showed no significance (n.s).

The wrist moments also had a 3-way interaction between sex, handedness, and direction ($F_{(2,54)}$= 3.42, p=0.0250) (Figure 9). All directions were significantly different other than the pull direction. The greatest difference was found in the right-handed males for the downward direction (wrist moment difference of 9.06 Nm). Right-handed female dominant arms showed greater wrist moment values mostly in the push, medial, and downward directions (wrist moment difference of 5.98 Nm, 3.83 Nm, & 4.75 Nm).

Figure 9. Wrist joint moment differences interaction between handedness, direction, and sex. Only the pull direction was non-significant (n.s).

3.3 Joint Angles

3.3.1 Shoulder Joint

The shoulder joint involves movements in three planes, axial rotation, glenohumeral elevation, and plane of elevation. Shoulder glenohumeral elevation is when the scapula moves in an upward direction, similar to moving the arms from the side of the body forward and up till the arms are beside the head. Shoulder joint angles at the different hand locations and directions are shown in Figure 10. The shoulder joint had general consistency across the difference hand location and direction conditions. This could be due to the fact the the protocol involved fixed hand positions. Right-handed individuals dominant arm had the greatest axial rotation of 12.4 degrees greater than their non-dominant limb (Figure 11). Smaller shoulder joint angles represented a greater externally rotated arm. Plane of elevation at the shoulder also had noticeable differences between hands. The greatest difference was noticeed at the shoulder hand location in the lateral diretion on the right-handed individuals, a difference of 13 degrees between hands (Figure 12). The non-dominant hand displayed larger angles indicating that it was closer to the mideline of the body.

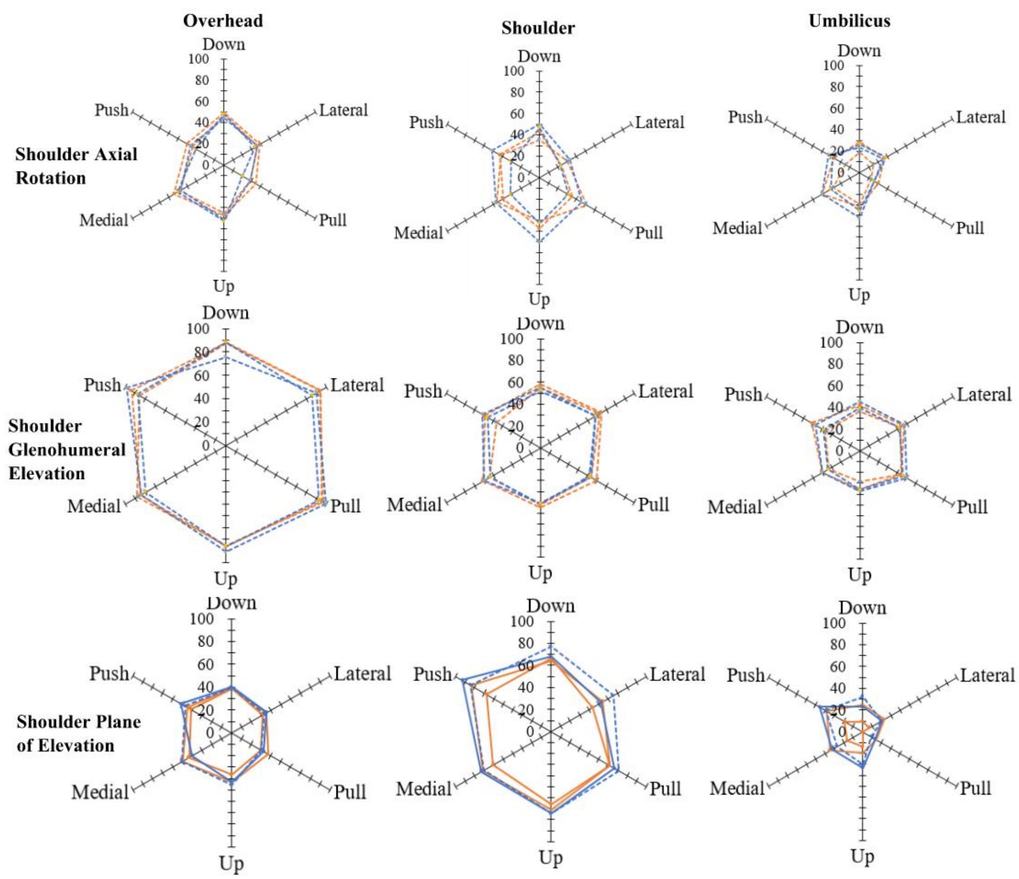


Figure 10. Raw shoulder joint angles in all 6 directions showing handedness and dominance average values. The orange lines represent the left-handed individuals and the blue lines represent the right-handed individuals. The dotted lines represent the non-dominant limbs.

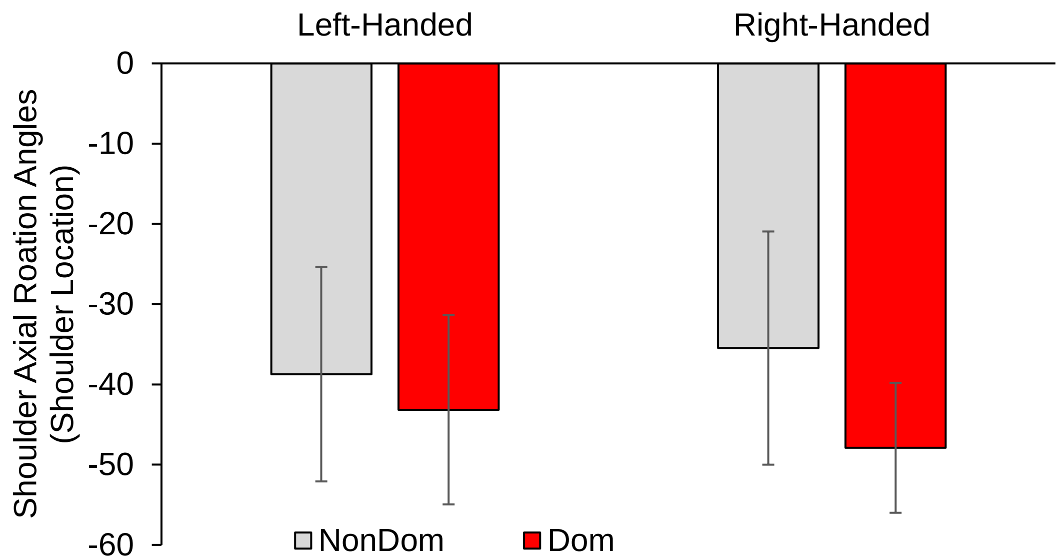
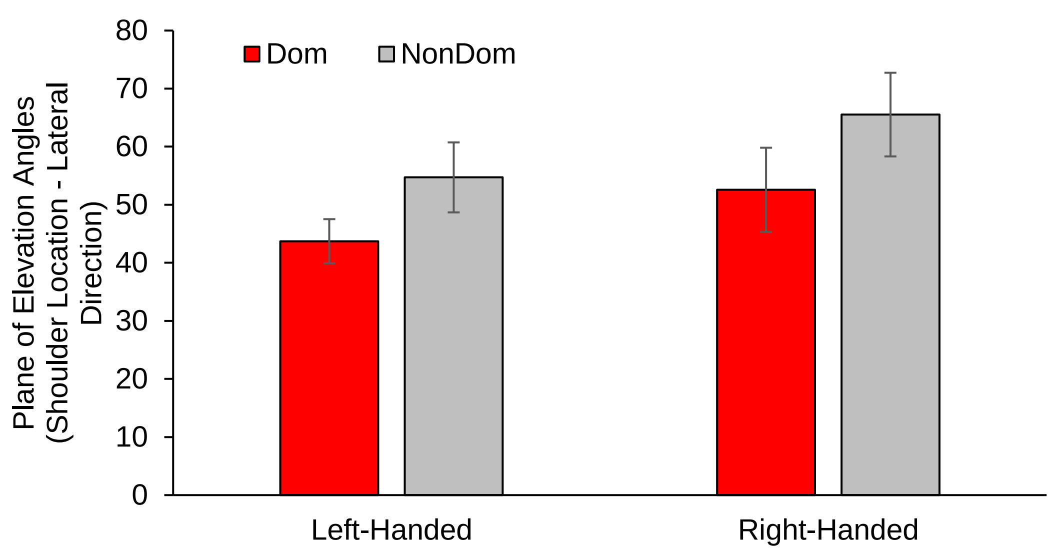


Figure 11. Average Axial Rotaion angles about the shoulder at the shoulder hand location compared between hands. red indicates the dominant hand and grey indicates the non-dominant hand. Error bars are shown.



Figrure 12. Average Plane of Elevation angles about the shoulder at the shoulder hand location and lateral direction compared between hands. Red indicates the dominant hand and grey indicates the non-dominant hand. Error bars are shown.

3.3.2 Elbow Joint

The Elbow joint performs pronation/supination and flexion/extension. Figure 13 presents the raw angles for each movement comparing the dominant and non-dominant between the right-handed individuals and the left-handed individuals. The pronation/supination posture stayed relatively consistent throughout the directions for both right-handed and left-handed individuals. Whereas, flexion/extension at the elbow had the most variability between hands (Figure 14). The dominant hand for right-handed individuals was 5 degrees different from the non-dominant limb. The more negative the angle the more extended the elbow is, meaning right-handed individuals had their dominant hand more extended than their non-dominant limb.

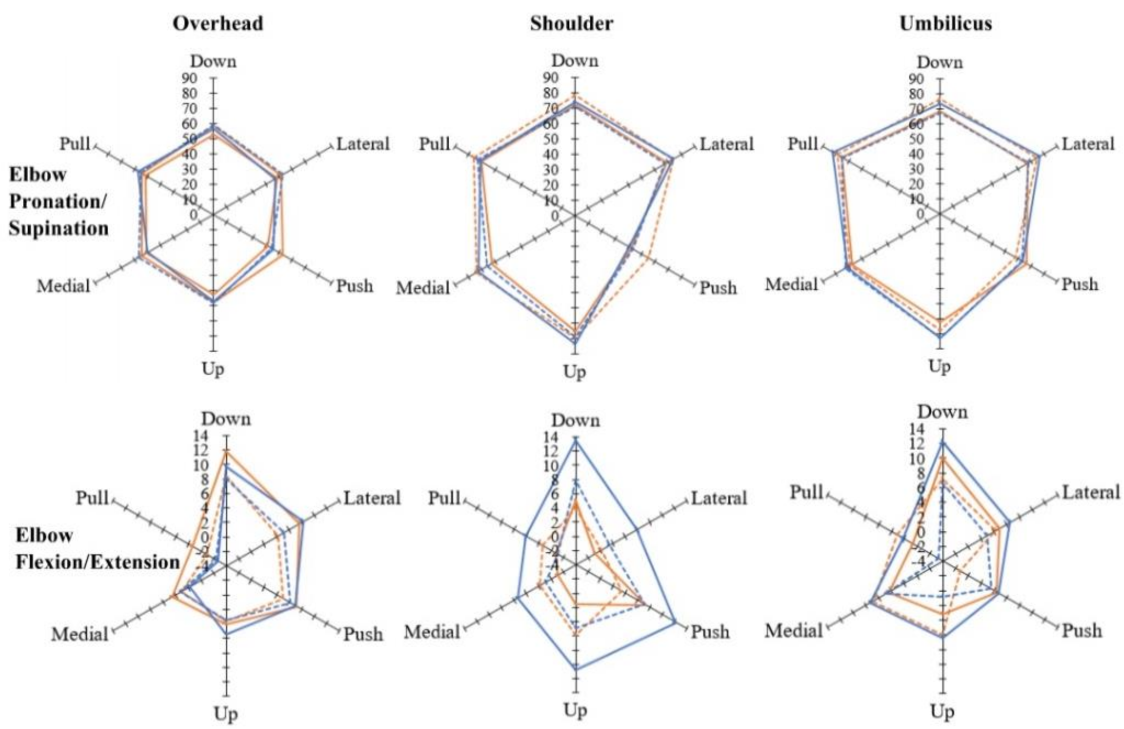


Figure 13. Raw elbow joint angles in all 6 directions showing handedness and dominance average values. The orange lines represent the left-handed individuals and the blue lines represent the right-handed individuals. The dotted lines represent the non-dominant limbs.

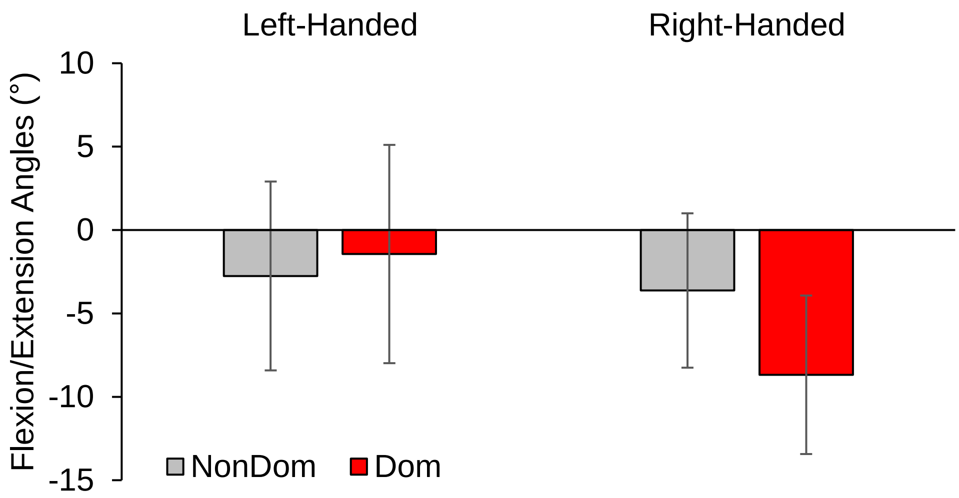


Figure 14. Flex/Ext angles at the shoulder hand location compared between hands. Red indicates the dominant hand and grey indicates the non-dominant hand. Error bars are shown.

3.3.3 Wrist Joint

The wrist joint performs flexion/extension and radial/ulnar deviation. Flexion/extension at the wrist joint angles has stayed relatively similar, the variability is noticed at the umbilicus hand location for radial/ulnar deviation (Figure 15). For both right-handed and left-handed individuals, the dominant limb was more radially deviated (difference angle of 6°) (Figure 16)

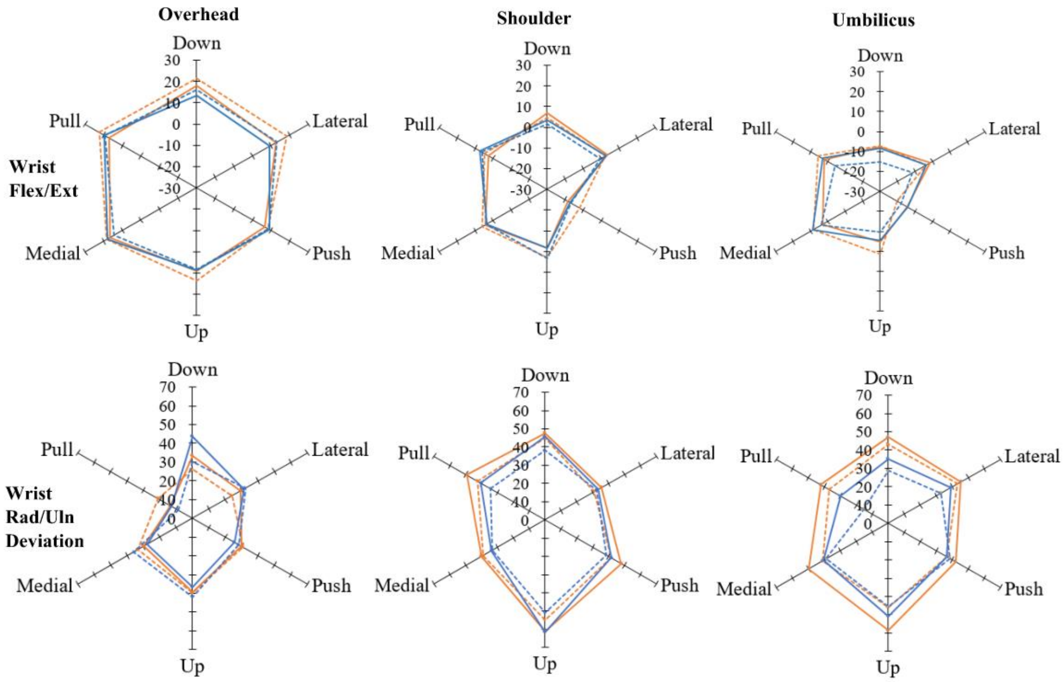


Figure 15. Raw wrist joint angles in all 6 directions showing handedness and dominance average values. The orange lines represent the left-handed individuals and the blue lines represent the right-handed individuals. The dotted lines represent the non-dominant limbs.

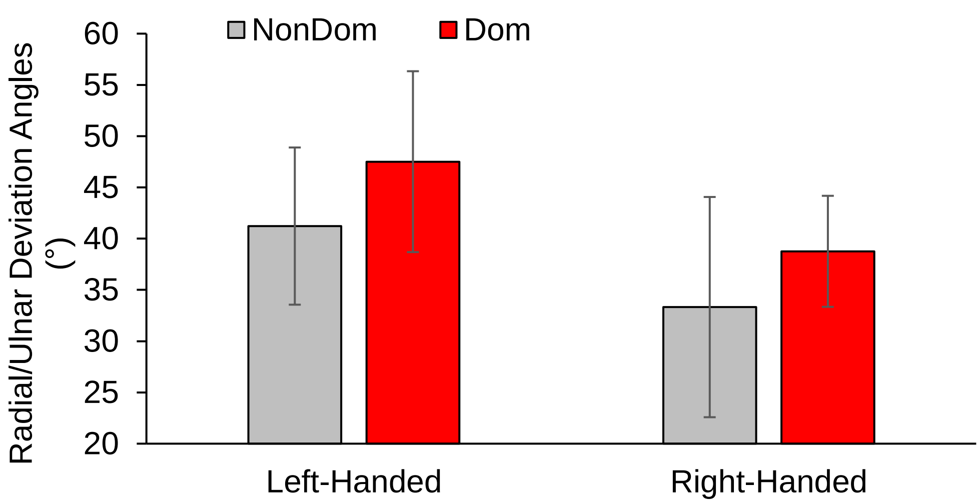


Figure 16. Radial/Ulnar deviation angles at the umbilicus hand location. Red indicates the dominant hand and grey in dicates the non-dominant hand.

4. Discussion

This study compared manual arm strength in both the dominant and non-dominant limbs in a variety of force direction and hand location conditions. In accordance with current handgrip research and ergonomics practices, we hypothesized that the dominant limb would be 10% stronger than the non-dominant limb (Yielder et al., 2009, Bohannon, 2003, Gutnik & Hyland, 1990, Armstrong & Oldham, 1999). This study also hypothesized noticeable differences between the upper limbs for joint moments and joint angles, based on suspected differences in motor control between limbs. In this study, moments were evaluated as a difference between dominant and non-dominant sides, given the number of moment degrees of freedom that were present across the upper limb. Larger differences represented potential strategic mechanical variations between the groups and experimental conditions.

The results of the study generally confirmed the hypothesis that the dominant limb was stronger than the non-dominant limb. Specifically, there were significant interactions and main effects involving handedness and dominance in the pull, medial and push directions. The joint moment data showed left-handed individuals had significantly different moment differences in all joints in comparison to right-handed individuals, pointing to strategic differences in maximum force production, not just the typically ascribed neurophysiological and biomechanical determinants of performance related to handedness. These results provide an understanding that overall strength difference between arms is minor, but when placed in certain positions and exerted in different directions, strength between arms changes (Hansen & Hallbeck, 1996; LaDelfa & Potvin, 2017; La Delfa, Evans, & Potvin, 2019). This was displayed when the main effect for dominance was shown for the pull and pull direction, also the data showed significant differences between the direction conditions when comparing hands between males and females.

Reiterating the results of the MAS values, both the right-handed individuals at the shoulder hand location and left-handed individuals at the umbilicus hand location had strength discrepancy of 23% in favor of the dominant hand for the pull exertion. This finding is interesting as the strength difference is the same, however the locations are different. Further research should be done on MAS looking at different intermediary hand locations to help understand these trends. In addition, right-handed individuals showed that their dominant hand is 10% stronger than their non-dominant which support previous research (Yielder et al., 2009, Bohannon, 2003, Gutnik & Hyland, 1990, Armstrong & Oldham, 1999). The left-handed individuals not showing this discrepancy also supports previous grip strength research, as many left-handed individuals are forced to use their right-hand (non-dominant) quite often due to living in a right-handed world, but this hypothesis remains anecdotal.

Some of the largest discrepancies in strength and joint moments between arms were observed for the push and pull directions. This could be due to the fact that push and pull exertions are more common exertions that are performed through day to day activities (Chaffin et al., 1983; Snook, 1978; Snook & Ciriello, 1991). Due to the familiarity of these exertion directions and their relatively higher magnitude, the strength output was larger which may serve to amplify differences in strength between arms. In addition, during pushing and pulling exertions the upper body is more active (De Looze et al., 2000). For example, during a push exertion the chest muscles are more activated and during a pull exertion the back muscles are more active.

Males were approximately 67% stronger than females in all exertion directions, which is similar to other published upper extremity strength data (Miller et al., 1993; Kanehisa, Ikegawa & Kukunaga, 1994; Bartolomei et al., 2021). We showed a main effect of sex for all directions which was expected due to the fact that male strength values are larger than females (Lopes et al., 2018; Roy et al., 2009). However, Male MAS was 20% stronger in their dominant arm in comparison to their non-dominant arm. Comparatively, females were much more balanced in strength between arms. Regarding shoulder moments, males dominant shoulder moment was 3 Nm stronger than their non-dominant. Whereas, for women the difference was only 1 Nm. There were slight postural differences between males and females, which could explain some of these discrepancies. For example, males had higher pronation at their dominant-arm elbow, which could drastically affect moment arms and the resulting manual arm strength (La Delfa & Potvin, 2016). Explanations for the differences in strength discrepancy between males and females are lacking. Further research should examine whether this is an important anthropometric difference, or an effect observed using this experimental approach for measuring arm strength.

On the topic of handedness, right-handed individuals showed greater shoulder moments on their dominant hand by 4 Nm. Whereas, the left-handed individuals shoulder joint moments were slightly larger on their non-dominant hand, roughly by 0.5 Nm. The discrepancies are miniscule yet expected as the experimental protocol was designed to isolate moment as much as possible, which was done by strapping down the shoulders. Surprisingly, the non-dominant arm in left-handed males was stronger for MAS, whereas, their dominant hand had larger shoulder moment differences.

Regarding joint angles, the data showed that the right-handed individuals' upper limbs were less flexed than the left-handed upper limbs, and even more so with their dominant limb. At the elbow joint, peak muscle force is typically generated at a range of approximately 90-140 degrees of flexion (Lieber & Boakes, 1988; Schmidt et al., 2014). For this study the arm was at 80% of their full arm reach meaning the elbow was more in an extended position. It is possible that the right-handed individuals had their elbow joint more flexed and their dominant hand closer to the optimal joint angle which helped produce a greater elbow moment. The wrist moments were more open to postural differences resulting in the significant findings. The pull exertion direction being insignificant was expected as a moment would not be applied when pulling straight out.

5. Limitations & Conclusion

This study involved some limitations that should be addressed. The data were collected on young and healthy university students between the ages of 18-30. Thus, further research is required to be done on other populations to fit the standard age of workforce employees. In addition, the experimental design involved isometric strength which is not fully representative of many work tasks which are more dynamic in nature. However, the protocol was set-up to allow for an accurate estimation of the MAS strength data for each exertion. Therefore, future studies should look at the discrepancies seen between hands on strength using dynamic contractions, especially given the different control strategies involved in dynamic vs static efforts, and potential differences in motor control between dominant and non-dominant limbs. Although we took every precaution to avoid fatigue by providing reasonable time to separate the exertions and altering sides, there were still a number of exertions conducted each day, with fatigue manifestation being likely. Stringent counter-balancing measures and rest time between trials were included to minimize any of these effects on the findings. Also, this was a relatively small sample in comparison to other studies looking at effects of handedness, though adequate power was obtained according to *a priori* assumptions. Future larger scale studies can be valuable to further confirm the group effects observed.

The majority of studies have analyzed strength differences between hands with mainly a right-hand population. Much can still be learned by further study within left-handed populations, which can translate to better and more accommodating designs for this segment of the population. In addition, the exertion directions in this study were perpendicular to each other, however, in regard of workplaces the exertions are not always in fixed directions. Thus, more strength data research should be done looking in to other possible directions where torque is also applied. Lastly, gathering more strength data at different hand locations will strengthen the estimates to create workplaces designs avoiding any risk.

This evaluation on the effect of hand dominance provided an important indication for the current assumptions made in ergonomics approaches. Future research should look at isometric strength differences at the individual joint levels (e.g. shoulder, elbow, wrist, etc) to further study any biomechanical or neuromechanical origins for any of the observed strength discrepancies. The 10 percent rule was shown to only be true towards the right-handed individuals. Further research should focus on strength data only on left-handed individuals to notice if there is a pattern noticed in their strength discrepancy. Females exhibited a more balanced strength difference, future studies should focus on seeing if there is any pattern noticed in males and females between hands. In addition, use of electromyography could help further elucidate any differences in neuromuscular control between dominant and non-dominant limbs for the same type of exertions.

6. References

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Chapter 4. General Discussion & Conclusions

1. Purpose & Rationale

In ergonomics task evaluation, strength capability is often used to guide acceptable force limits for manual tasks to lower the risk of musculoskeletal injury (Chaffin, 1997); however, the available upper limb strength data rarely considers strength capability of the non-dominant or left arm. The central question of this thesis examines how occupationally relevant upper extremity strength differs between the dominant and non-dominant limbs. Strength differences due to handedness were evaluated through functional manual force exertions. A secondary objective of this project was to examine the relationship between the individual joint moments and joint angles during manual arm strength exertions.

The Arm Force Field (AFF) method (La Delfa & Potvin, 2017) is a novel approach to estimate manual arm strength in several workplace scenarios and is currently being utilized in several proactive digital human modeling software platforms (e.g. SantosHuman & Jack). Despite its integration into the proactive ergonomics process to estimate acceptable hand loads, the AFF still relies on several assumptions. For example, all data used in the creation of the AFF only included one-handed strength measures from the dominant arm. This does not account for many occupational scenarios where the non-dominant arm is involved in the task. The current assumption, utilized by ergonomics modeling software, is that the left limb has approximately 90% of the strength of the right limb; however, there is little evidence supporting the validity of this assumption (Demura, Miyaguchi, & Aoki, 2010).

The study of hand-dominance or hand of exertion, with respect to manual arm strength capability, represents an important progression in the AFF method. Furthermore, this study provided us with an opportunity to compare differences in joint kinetics and kinematics between limbs during manual exertions, which is a relatively underexplored area of strength assessment in ergonomics. We will work together with our industrial partner (SantosHuman Inc) to ensure these research outcomes will be installed in future iterations of the AFF method, and in turn, serve to improve future estimation of acceptable forces when the non-dominant arm is involved.

2. Key Findings

Our results show that the '10% rule', which states that the dominant limb is generally 10% stronger than the non-dominant limb, holds true for manual arm strength exertions in multiple directions and hand locations. However, it should be noted that while the 10% generally holds true on a population level, it differs when handedness is considered a factor. This study showed the '10% rule' is primarily driven by right-handers, who showed a 13% stronger dominant limb, whereas left-handers demonstrated relatively even strength distribution between limbs. Similarly, the 10% rule did not ubiquitously apply for every exertion direction or hand location, with the push and pull directions showing the greatest discrepancy between arms. These results indicate manual arm strength capability between arms is task-dependent, so simple application of a ~10% strength correction for the non-dominant limb may not be appropriate in all circumstances.

Further to the strength ratio between dominant and non-dominant hands, proportion of stronger hand statistics also showed drastic group differences. The non-dominant hand was stronger in 41% of the overall conditions, 46% for males and 36% for females. This study also strengthened previous research that, on average, females have roughly 65% of the upper limb strength capability of males. Finally, left-handed participants had significantly different joint moment profiles from right-handed participants between the exertion directions tested in this thesis. These individual joint moment data suggest that differing motor control strategies between right- and left-handed individuals could explain discrepancies in force capability between the hands observed at the different hand locations.

3. General Limitations & Future Directions

The study assessed manual arm strength in an isometric experimental protocol which is not the best representation of the various tasks seen at workplaces, the physical work is more dynamic. Thus, future studies should try to examine physical strength in a more dynamic setting that represents occupational tasks more closely. Furthermore, the sample age group was relatively younger than the common working population, this could be re-examined by collecting data from a working population.

This study will enhance our ability to understand strength capability in ergonomics assessments and provide ergonomists with a better appreciation for how handedness can impact ergonomics task assessments and potential injury risk. There should be more focus on collecting data on only left-handed individuals to see if there is a pattern similar to the

10% rule noticed in right-handed individuals. This is due to the fact that this study showed left-handed individuals to be more balanced than right-handed individuals. Additionally, it would be interesting to compare ambidextrous and left-handed strength to see how much they differ between groups. As ambidextrous individuals are predicted to have balanced strength. There were noticeable differences between sexes however nothing concrete. Future studies should look at handedness between sexes to see if there are any significant findings that can be stated and by incorporating these findings within the Arm Force Field method, which is currently used in several digital human modeling software packages around the world to conduct proactive ergonomics assessments.

4. Final Recommendations

As such, this research will be utilized by practitioners to refine their estimates of manual force capability and injury risk, and has the potential to reduce the burden of injury risk within our population. Importantly, these research findings can be directly translated to industry, by incorporating these findings within the Arm Force Method, HandPak (Potvin Biomechanics Inc.), or any upper extremity strength data.

Regarding the evident strength discrepancy between arms, workplaces should avoid having tasks that is only engineered for one hand. If it is compatible for either hand it allows the individual to chose which hand they prefer but also to switch arms when it becomes fatiguing. On the other hand, ergonomists could refine their threshold limits towards non-dominant strength in order to accommodate for everyone whether they are right-handed or left-handed. Furthermore, designing stations that have the individual working overhead should lower the load as the strength output shown in the overheard location was lower than the shoulder and umbilicus hand location. The familiarity of the push and pull directions allowed for greater strength output, hence focussing on designing workplaces where the tasks involve exertions in those directions allows for a more proficient place of work.

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APPENDICES

APPENDIX A. INFORMED CONSENT - STUDY 1

Consent Form to Participate in a Research Study

Title of Research Study: The effect of handedness on manual arm strength and upper-extremity isometric joint strength.

Name of Principal Investigator (PI): Dr. Nicholas La Delfa

PI's contact number(s)/email(s): 905-721-8668 ext 2139 / nicholas.ladelfa@uoit.ca

Names(s) of Co-Investigator(s), Faculty Supervisor, Student Lead(s), etc., and contact number(s)/email(s):

1. Fahima Wakeely, MHSc Student (fahima.wakeely@ontariotechu.net);

2. Michael Watterworth, Undergraduate Student (michael.watterworth@ontariotechu.net)

3. Sarah Norman, Undergraduate Student (sarah.norman@ontariotechu.net)

4. Ellen Dalgarno, Undergraduate Student (ellen.dalgarno@ontariotechu.net)

Departmental and institutional affiliation(s): Faculty of Health Sciences, Ontario Tech University

External Funder/Sponsor: none

Introduction

You are invited to participate in a research study entitled "*The effect of handedness on manual arm strength and upper-extremity isometric joint strength"*. You are being asked to take part in a research study. Please read the information about the study presented in this form. The form includes details on study's procedures, risks and benefits that you should know before you decide if you would like to take part. You should take as much time as you need to make your decision. You should ask the Principal Investigator (PI) or study team to explain anything that you do not understand and make sure that all of your questions have been answered before signing this consent form. Before you make your decision, feel free to talk about this study with anyone you wish, including your friends and family. Participation in this study is voluntary.

This study has been reviewed by the University of Ontario Institute of Technology (Ontario Tech University) Research Ethics Board [REB #8963] on [insert date].

Purpose and Procedure:

Purpose:

In the field of ergonomics, estimation of manual arm strength has been used to design manual tasks to lower the risk of musculoskeletal injury (La Delfa et al., 2014). Manual arm strength refers to the maximal force that can be exerted by the hand in any given direction. The Arm Force Field method established by La Delfa & Potvin, (2017) is a novel method to estimate manual arm strength in several workplace scenarios and is currently being utilized in several ergonomics tools.

Though the Arm Force Field has since become a preferred method to estimate acceptable hand loads in industry, it is still prone to several limitations and makes several assumptions. For example, all data used in the creation of the Arm Force Field only included one-handed strength measures from the dominant limb. This does not account for many occupational scenarios where the non-dominant limb is involved in the task.

The study of hand-dominance, with respect to manual arm strength capability, can provide fundamental contributions to how acceptable manual forces are utilized in industry. As such, the **purpose** of this research is to examine how manual arm strength differs between dominant and non-dominant limbs in several hand location and force direction combinations, as well as determine the relationship between upper extremity isometric joint strength and manual arm strength, specifically determining the limiting joints for various force exertions and postures.

Specific objectives of this study are to: 1) determine the differences in manual arm strength between dominant and non-dominant limbs; 2) determine the relationship between upper extremity joint strength and manual arm strength, and determine if the limiting joint can reliably be predicted, 3) determine if there is a difference in joint kinematics and kinetics between limbs during manual arm strength isometric joint strength tests, 4) evaluate if any of the above differences are affected by sex and/or handedness.

You have been invited to participate in this study because you are free from upper extremity (shoulder, elbow, wrist) pain or disorders, and therefore meet the required criteria for participation.

Procedures:

Upon arriving at the laboratory (UAB 355 and J101-B), you will be asked to review this consent form and provide written and oral consent once you are fully satisfied with what this study involves. At this point, we will ask you to change into loose fitting exercise clothing that provides access to your upper back and both arms. Before the study begins, physical characteristics (e.g. height, weight, age, and arm lengths) will be measured. The data obtained will be kept confidential. You will be given at least three days of rest between visits.

Table 1: Visiting Procedures

Visit	Study procedure/tests/interventions	Duration of visit
Visit 1*	Manual Arm Strength	3 hours
Visit 2*	Isometric Joint Strength	3 hours

*Please note, the particular order of conditions will be randomized. Therefore, on your Visit #1, you may actually perform the ‘Isometric Joint Strength Exertions’. All conditions will be completed by the end of the study.

Manual Arm Strength Collection (Visit 1 or 2, depending on random order)

On the Manual Arm Strength Visit, you will report to the Occupational Neuromechanics and Ergonomics Laboratory (UAB 355). You will be instrumented with some non-invasive sensors so we can track the movement of your upper-extremities. We will also ask you to tie your hair up into a bun or pony-tail, if necessary, so it does not interfere with the sensors on your back. Seven ***infrared emitting diodes (IREDs)*** will be affixed to your torso (upper back) and onto both arms. These IRED sensors emit infrared light that are picked up by specialized motion capture cameras and allow us to determine your upper body posture in 3-D space. Since these only capture infrared light from the IREDs, you will not be discernable in any form by these cameras, which solely output 3D coordinates of the IRED sensors. These IRED sensors will be affixed to your skin using tape, and this will take approximately 15 minutes to set up.

After fully instrumented with the motion capture IRED sensors, you will then begin the Manual Arm Strength measurements. You will be exerting forces maximally while grasping a vertically oriented handle that is affixed to a force transducer. This apparatus will be used to measure the forces and torques you exert on the handle. You will be sitting and secured (using seatbelt straps) in a chair in front of the handle. For the protocol, we will ask you to apply your maximum amount of force to the handle, also known as maximum voluntary force exertions (MVFs). The handle will be located in 3 different positions of differing heights and angles relative to your shoulder (Shoulder height at 0° - directly in front of you, Umbilicus height at 45°, and Overhead at 45° - both angled to your right). You will be asked to exert your MVFs in 6 different directions (up, down, push, pull, left, right). Each MVF trial will last 5 seconds in duration. You will perform these exertions twice each with your right arm and twice again with your left arm. The handle position, direction of exertion, and arm performing the exertion will be occur in a randomized order. You will be given 3-6 familiarization trials prior to your first condition to get you comfortable with the setup. In total for this visit, you will be performing 72 MVFs (excluding familiarization) - 36 exertions with your right arm and 36 exertions with your left arm. It is vital these exertions are truly as hard as you can exert. At least one minute of rest will be given between every exertion to ensure adequate recovery.

Isometric Joint Strength Collection (Day 1 or 2, depending on random order)

On the Isometric Joint Strength Visit, you will report to the Kinesiology Undergraduate Laboratory (J101-B). Collections will be held in this location so we can utilize the specialized strength measurement device known as the HUMAC NORM Testing and Exercise System (Figure 1). There will be 7 postures that you will be asked to assume. Each posture will isolate a particular joint's plane of movement, in order to assess the isometric strength of your shoulder, elbow, and wrist joints. 'Isometric' means that the exertions occur with no movement. The HUMAC NORM is specifically designed for these sorts of maximum strength tests, and have several safety features built in. When performing exertions, you will be harnessed to the chair in the required posture and perform two trials of two different maximum voluntary contractions (MVCs). Before each posture's MVC, a familiarization trial will be done to facilitate your understanding of the task. Each MVC trial will last 5 seconds.

Following the HUMAC NORM testing, a hand force dynamometer will be used to measure your grip strength in both hands. You will be asked to sit with your shoulder adducted to the side of the body, elbow flexed to 90°, and forearm and wrist neutral. You will then be asked to squeeze the grip dynamometer as hard as possible. This will occur twice with each arm, with adequate rest in between. Again, each exertion will last 5 seconds.

Figure 1: HUMAC NORM Testing and Exercise System - dynamometer manufactured by Computer Sports Medicine Inc. (CSMi).

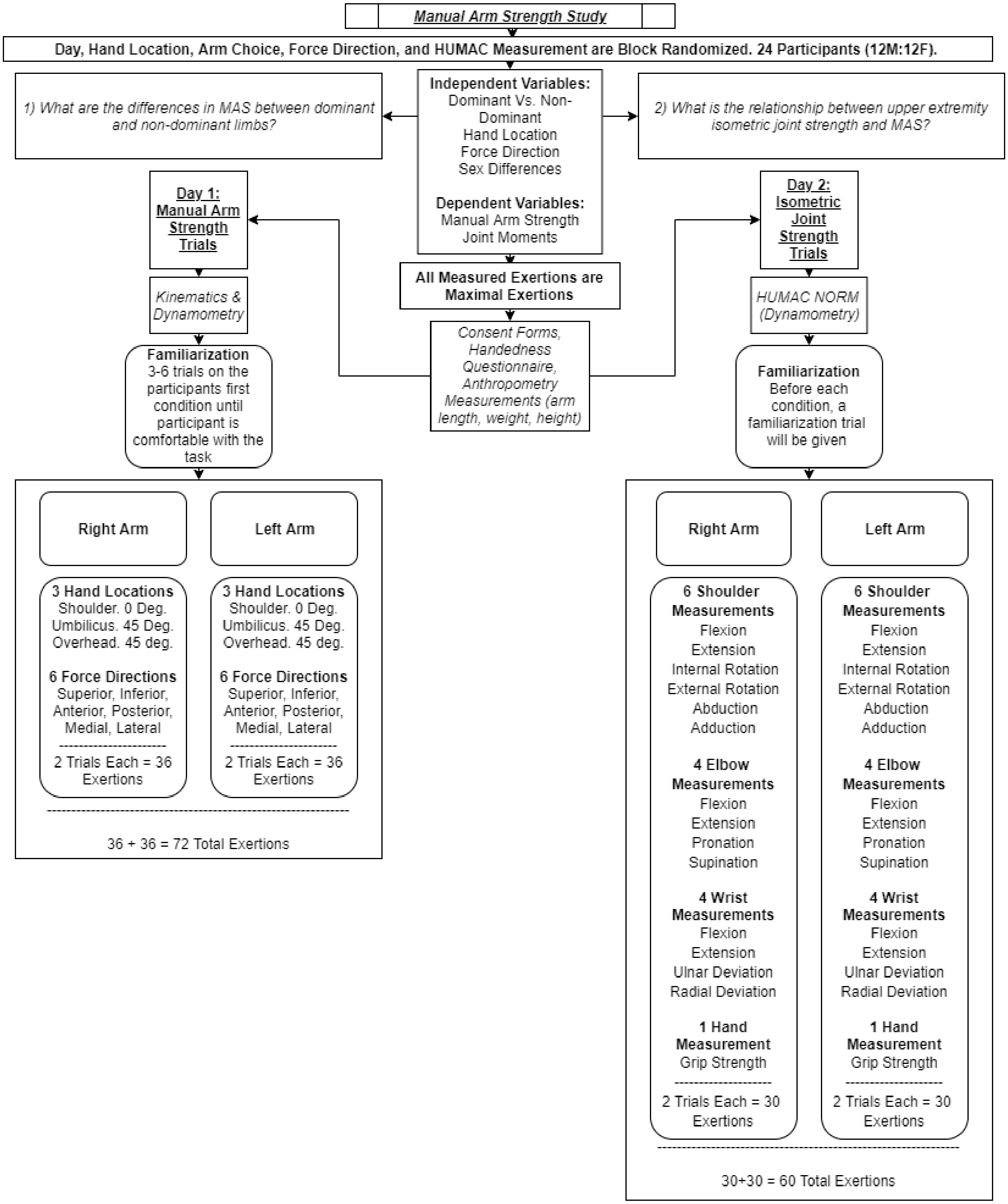

Figure 2: Flow Chart of Experimental Protocol

Potential Benefits:

You will not *directly* benefit from participating in this study. However, by participating, you will be contributing to our scientific knowledge on how manual arm strength differs between dominant and non-dominant arms, and whether isometric joint strength and manual arm strength possess a relationship with each other. The outcomes from this research will directly inform ergonomics tools that are used by industries all over the world.

Potential Risk or Discomforts:

A vital aspect of this study is to measure maximal exertion, which commonly results in a localized fatigue of the muscles in the upper extremities. This is the same sensation you may feel when working out at the gym or picking up and carrying something heavy. This fatigue is due to exerting force via the muscles. In the event that this discomfort becomes too severe, notify the investigators immediately. Remember that you are able to withdraw and/or take a break from the study at any time, for any reason, without penalty. Note that in the end you are in direct control of the amount of force being applied. You should not feel obligated to continue with the testing protocol if you are in severe discomfort, as our first priority is your safety. That said, the task may be mildly uncomfortable. As such, we may ask you to tell us your comfort levels at regularly occurring intervals. To avoid this discomfort, plenty of resting time will be given between conditions.

Secondly, the process of taping the kinematic markers pose an extremely slight risk of skin irritation from the tape's adhesive. These reactions are not significant and they generally subside within 1-3 days. Participants will to wash and clean the area with soap where the tape was applied to mediate the problem. However, if the irritations continue to be a problem, we recommend that the participant proceed to the campus health clinic for advice regarding the irritations and contact the researchers to report the incident.

Use and Storage of Data:

All collected data will be initially stored on a password protected computer in the Occupational Neuromechanics & Ergonomics (ONE) Laboratory, then moved to an encrypted and password protected hard drive, which will be stored in a locked filing cabinet in the ONE lab. All data will also be backed up on an encrypted and password protected Google Drive administered by Ontario Tech University and approved by our REB. All digital experimental data will be identified with a randomly assigned participant code.

All participant consent forms, questionnaires and any other potential identifying information (e.g. sex, age and anthropometric data) will be locked in a separate location; a locked filing cabinet in Dr. La Delfa's secure office. All consent forms, questionnaires and identifying information will be retained for a period of 2 years before being destroyed. Due to the nature of this research and evolving development of the Arm Force Field method, all anonymized experimental data will be retained indefinitely. However, once all identifying information is destroyed after 2 years, we will have no way of linking your data with you. Please note that if your data is considered for use in a secondary analysis, we will seek appropriate REB approval before undertaking this analysis. Additionally, we will ask for your pre-consent to use these data in a potentially secondary analysis, in case this analysis occurs after the period of 5 years and we lose the ability to identify your data. All information collected during this study, including your demographic and anthropometric data, will be kept confidential and will not be shared with anyone outside the study unless required by law. You will not be named in any reports, publications, or presentations that may come from this study.

Confidentiality:

Your privacy shall be respected. No information about your identity will be shared or published without your permission, unless required by law. Confidentiality will be provided to the fullest extent possible by law, professional practice, and ethical codes of conduct. Please note that confidentiality cannot be guaranteed while data is in transit over the Internet.

This research study includes the collection of demographic data which will be aggregated (not individually presented) in an effort to protect your anonymity. Despite best efforts it is possible that your identity can be determined even when data is aggregated. However, we will minimize the potential of this occurrence by refraining from presenting any individual data points (for example in a scatter plot where any identifying information is presented on one axis). In practice, we typically only present mean and standard deviation data, which will make it impossible to identify one particular participant in our research.

Voluntary Participation:

Your participation in this study is voluntary and you may partake in only those aspects of the study in which you feel comfortable. You may also decide not to be in this study, or to be in the study now, and then change your mind later. You may leave the study at any time without affecting your academic standing, and/or research credit. You will be given information that is relevant to your decision to continue or withdraw from participation. Such information will need to be subsequently provided.

Right to Withdraw:

Your participation in this study is strictly voluntary and you are free to withdraw at any point without providing a reason. Throughout the research process, you are free to withdraw from participation at any time without repercussions. If you withdraw from the research project at any time, any acquired experimental data will be destroyed and removed from the study.

Conflict of Interest:

Researchers have an interest in completing this study. Their interests should not influence your decision to participate in this study.

Compensation, Reimbursement, Incentives:

As compensation for your time spent participating in this study, you have the right to select one (1) of two (2) potential forms of reimbursement. You may select either:

1. a 10$ Tim Hortons gift card; or
2. a 2% mark added to the Health Sciences course of your choosing (must be from the list of pre-confirmed course options, which we will provide)

Your participation in this study will not have any direct expense associated to you.

Debriefing and Dissemination of Results:

The data for this research may be submitted to scientific conferences and peer-reviewed journals for publication. Any published data will be free of any potentially identifying information. If you wish to receive an aggregate of the research findings, please check the box at the bottom of this form and provide an email address to receive the results.

Participant Rights and Concerns:

Please read this consent form carefully and feel free to ask the researcher any questions that you might have about the study. If you have any questions about your rights as a participant in this study, complaints, or adverse events, please contact the Research Ethics Office at (905) 721-8668 ext. 3693 or at researchethics@uoit.ca.

If you have any questions concerning the research study or experience any discomfort related to the study, please contact Fahima Wakeely at fahima.wakeely@ontariotechu.net or Dr. Nicholas La Delfa at nicholas.ladelfa@uoit.ca. By signing this form you do not give up any of your legal rights against the investigators, sponsor or involved institutions for compensation, nor does this form relieve the investigators, sponsor or involved institutions of their legal and professional responsibilities.

<u>Consent to Participate:</u>

1. I have read the consent form and understand the study being described;
2. I have had an opportunity to ask questions and those questions have been answered. I am free to ask questions about the study in the future;
3. I freely consent to participate in the research study, understanding that I may discontinue participation at any time without penalty. A copy of this consent form has been made available to me.

____

Print Study Participant's Name Signature Date

My signature means that I have explained the study to the participant named above. I have answered all questions.

____

Print Name of Person Obtaining Signature Date

Secondary Use of Research for Future Research Purposes

1. I understand the possible need for secondary research uses of my research data for future research use and provide consent for the use of my data to be used in future studies.
2. The research team has informed me that a separate REB application will be submitted for the secondary use of data for any future research purposes.

Participant must initial _________ Yes _________No

APPENDIX B. EDINBURGH HANDEDNESS INVENTORY

Surname_____________________ Given Name _____________________________

Date of
Birth____________________________Sex_________________________________

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

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

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

	Left	Right
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking Match (match)		
10. Opening box (lid)		
L.Q. Leave the spaces blank	DECLE	

APPENDIX C: PARTICIPANT DEMOGRAPHIC

OntarioTech UNIVERSITY

Participant Information:

Title: The effect of handedness on manual arm strength and upper-extremity isometric joint strength.

This study has been approved by the UOIT Research Ethics Board REB [#8963] on DATE HERE. Please note the data collected on this form will be stored separately from your experimental data and locked in a secured filing cabinet.

If you would like a copy of this consent form for your records, please ask the investigators.

Received Copy: ***YES*** ☐ ***NO*** ☐

Name: ____

Biological Sex (circle one): **Male** **Female**

Date of Birth: ______________________________ **Current Age:** __________

Email Address: ____

Have you experienced upper extremity pain in the last 6 months?	**YES** ☐	**NO** ☐
Have you ever had upper arm/forearm surgery?	**YES** ☐	**NO** ☐
Would you like to be notified with the aggregate results of the study when they are released in summer of 2020 via email?	**YES** ☐	**NO** ☐
I hereby give consent for the information contained in this package to be used for the purposes of this study and in future research as long as there is no way that I can be identified.	**YES** ☐	**NO** ☐

Anthropometric Data to be collected by Experimenters:

Height (cm): ______ **Mass (kg):** ______ **Arm Length (cm):** _____ **Shoulder height (cm):** ______

If you have any questions concerning the research study, please contact the researcher Fahima Wakeely at fahima.wakeely@ontariotechu.net . Alternatively, you can contact the principal investigator Dr. Nicholas La Delfa at 905.721.8668 x2139 or nicholas.ladelfa@uoit.ca.

Any questions regarding your rights as a participant, complaints or adverse events may be addressed to Research Ethics Board through the Research Ethics Coordinator –researchethics@uoit.ca or 905.721.8668 x. 3693.

________________________________ ______________________________

Participant Signature **Date**

APPENDIX D: JOINT MOMENTS AND MAS RAW VALUES

Moments		Right-Handed		Left-Handed	
		Dominant	*Non-Dominant*	*Dominant*	*Non-Dominant*
Shoulder Joint					
Overhead	Down	58.71 ± 25.31	59.46 ± 21.25	71.57 ± *48.68*	61.50 ± *38.81*
	Lateral	36.47 ± 17.32	45.91 ± 18.27	42.39 ± *19.79*	35.37 ± *24.38*
	Medial	37.21 ± *23.73*	33.77 ± *16.86*	37.45 ± *23.98*	39.70 ± *27.76*
	Pull	32.28 ± *18.66*	33.24 ± *15.69*	37.30 ± *16.52*	29.64 ± *17.29*
	Push	46.77 ± *24.48*	47.30 ± *20.58*	53.75 ± *30.59*	33.23 ± *26.57*
	Up	21.69 ± *14.76*	19.50 ± *10.89*	26.44 ± *14.98*	29.25 ± *33.36*
Shoulder	Down	76.34 ± *24.06*	76.12 ± *28.12*	86.03 ± *49.64*	63.90 ± *36.41*
	Lateral	38.67 ± *19.65*	39.58 ± *15.61*	37.73 ± *19.41*	34.71 ± *19.49*
	Medial	46.03 ± *21.96*	41.03 ± *18.68*	42.86 ± *24.10*	42.31 ± *22.38*
	Pull	30.91 ± *20.77*	24.88 ± *11.45*	32.00 ± *25.51*	27.39 ± *20.43*
	Push	28.42 ± *20.76*	33.64 ± *51.13*	27.17 ± *29.09*	24.15 ± *20.29*
	Up	43.27 ± *34.65*	26.59 ± *12.67*	30.38 ± *15.80*	33.25 ± *27.50*
Umbilicus	Down	67.34 ± *22.05*	51.14 ± *31.83*	60.33 ± *36.65*	59.53 ± *35.94*
	Lateral	33.70 ± *11.60*	34.03 ± *16.19*	30.89 ± *20.17*	32.59 ± *19.89*
	Medial	44.84 ± *13.25*	37.86 ± *19.01*	42.88 ± *33.64*	45.50 ± *30.44*
	Pull	41.25 ± *20.04*	38.68 ± *11.82*	48.44 ± *25.15*	36.62 ± *21.26*
	Push	51.92 ± *37.99*	33.36 ± *20.30*	39.97 ± *39.86*	37.96 ± *25.24*
	Up	39.05 ± *13.00*	34.37 ± *14.26*	32.72 ± *21.83*	38.41 ± *35.46*
Elbow Joint					
Overhead	Down	20.32 ± 10.55	19.26 ± 9.74	22.86 ± 15.86	24.92 ± 14.95
	Lateral	21.15 ± 12.28	27.08 ± 10.34	25.06 ± 10.35	20.62 ± 12.50
	Medial	26.26 ± 16.84	24.33 ± 10.71	26.60 ± 10.74	31.01 ± 15.74
	Pull	13.91 ± 9.91	15.56 ± 8.82	16.65 ± 12.18	16.42 ± 9.57
	Push	22.98 ± 15.24	26.56 ± 13.09	33.71 ± 27.36	19.89 ± 13.83
	Up	11.40 ± 9.17	9.23 ± 6.68	13.47 ± 6.95	18.26 ± 30.89
Shoulder	Down	32.68 ± 12.41	32.46 ± 12.82	44.29 ± 37.17	33.25 ± 20.04
	Lateral	20.72 ± 11.94	20.36 ± 9.37	20.42 ± 12.27	19.36 ± 12.05
	Medial	28.15 ± 14.51	24.95 ± 11.05	27.07 ± 15.08	33.10 ± 18.33
	Pull	35.44 ± 16.69	34.45 ± 12.24	29.94 ± 15.66	30.54 ± 15.70
	Push	35.61 ± 17.22	44.81 ± 47.36	33.29 ± 26.00	33.94 ± 16.73
	Up	31.45 ± 35.73	14.43 ± 6.83	17.86 ± 9.42	22.87 ± 25.10
Umbilicus	Down	41.39 ± 14.32	33.05 ± 19.94	39.56 ± 23.85	40.74 ± 22.09
	Lateral	27.83 ± 9.61	26.41 ± 12.38	25.00 ± 12.95	26.14 ± 15.04
	Medial	35.76 ± 11.74	30.25 ± 13.93	30.90 ± 20.94	32.57 ± 18.23
	Pull	15.72 ± 6.41	19.40 ± 6.79	20.11 ± 13.12	15.97 ± 14.60
	Push	32.87 ± 36.81	16.09 ± 10.64	18.41 ± 19.75	22.10 ± 19.60
	Up	32.28 ± 12.50	27.67 ± 13.79	29.65 ± 19.74	34.82 ± 32.95
Wrist Joint					
Overhead	Down	7.22 ± *4.36*	2.85 ± *3.29*	6.30 ± *6.87*	7.95 ± *4.84*
	Lateral	4.51 ± *3.11*	2.18 ± *2.43*	3.62 ± *3.20*	3.99 ± *2.70*
	Medial	5.16 ± *3.33*	1.84 ± *2.08*	4.20 ± *3.92*	6.05 ± *3.86*
	Pull	1.94 ± *1.55*	1.15 ± *1.46*	1.76 ± *1.57*	2.18 ± *1.26*
	Push	5.70 ± *3.00*	2.55 ± *2.61*	12.16 ± *28.85*	4.06 ± *2.90*
	Up	3.40 ± *2.19*	1.23 ± *1.33*	2.99 ± *2.78*	12.16 ± *31.07*
Shoulder	Down	8.64 ± *3.63*	3.01 ± *3.08*	17.28 ± *39.17*	7.97 ± *5.08*
	Lateral	4.75 ± *2.57*	1.88 ± *2.05*	3.30 ± *3.40*	4.40 ± *2.52*
	Medial	6.23 ± *3.15*	2.32 ± *2.29*	4.52 ± *4.20*	6.60 ± *3.15*
	Pull	4.33 ± *5.82*	2.26 ± *2.08*	2.53 ± *2.09*	2.94 ± *2.31*
	Push	14.14 ± *9.64*	19.73 ± *52.19*	8.14 ± *8.39*	8.65 ± *6.76*
	Up	21.02 ± *37.57*	1.67 ± *1.66*	3.48 ± *3.38*	11.80 ± *26.83*

Umbilicus	Down	8.83 ± *3.84*	1.44 ± *1.94*	5.92 ± *6.16*	8.08 ± *4.70*
	Lateral	5.86 ± *1.92*	2.27 ± *2.57*	3.74 ± *3.49*	9.23 ± *16.32*
	Medial	8.19 ± *2.98*	2.98 ± *3.26*	5.28 ± *6.11*	7.13 ± *4.12*
	Pull	4.60 ± *2.70*	3.08 ± *3.72*	2.94 ± *3.03*	3.65 ± *2.50*
	Push	20.81 ± *39.74*	2.79 ± *3.52*	6.04 ± *8.74*	8.79 ± *5.41*
	Up	7.41 ± *2.98*	3.06 ± *3.26*	4.91 ± *5.06*	15.31 ± *33.16*

<u>MAS</u>		**Right-Handed**		**Left-Handed**	
		Dominant	Non-Dominant	Dominant	Non-Dominant
Overhead	Down	151.6 ± *58.3*	148.7 ± *51.9*	173.8 ± *104.3*	166.5 ± *90.2*
	Lateral	87.9 ± *28.0*	86.8 ± *30.0*	85.2 ± *31.0*	83.9 ± *24.8*
	Medial	102.7 ± *35.1*	92.5 ± *21.8*	99.1 ± *41.3*	110.5 ± *52.1*
	Pull	138.6 ± *43.3*	148.6 ± *46.7*	157.2 ± *105.4*	144.1 ± *65.5*
	Push	154.0 ± *50.6*	162.7 ± *57.4*	163.6 ± *63.0*	145.8 ± *59.3*
	Up	80.0 ± *26.0*	74.3 ± *25.6*	81.0 ± *29.0*	89.7 ± *35.3*
Shoulder	Down	154.5 ± *58.5*	146.8 ± *59.0*	157.8 ± *79.5*	145.0 ± *69.8*
	Lateral	87.2 ± *33.3*	83.2 ± *29.2*	81.3 ± *32.3*	82.2 ± *30.2*
	Medial	105.2 ± *39.0*	93.2 ± *29.2*	101.5 ± *39.9*	102.9 ± *45.8*
	Pull	306.2 ± *122.2*	247.2 ± *78.0*	257.8 ± *130.3*	245.7 ± *129.3*
	Push	339.3 ± *145.4*	296.2 ± *145.4*	292.5 ± *168.5*	271.9 ± *151.7*
	Up	93.9 ± *42.9*	76.4 ± *30.7*	86.5 ± *35.4*	86.4 ± *36.8*
Umbilicus	Down	128.8 ± *44.7*	125.5 ± *39.3*	125.4 ± *67.0*	130.3 ± *58.7*
	Lateral	95.0 ± *28.2*	85.2 ± *29.1*	85.0 ± *37.1*	78.9 ± *29.5*
	Medial	134.4 ± *40.8*	118.3 ± *30.0*	128.0 ± *65.7*	129.9 ± *61.3*
	Pull	209.9 ± *74.5*	200.5 ± *43.9*	228.4 ± *125.1*	185.5 ± *87.0*
	Push	229.7 ± *90.9*	195.2 ± *63.7*	224.9 ± *171.8*	223.8 ± *158.1*
	Up	113.6 ± *37.4*	103.2 ± *41.0*	110.1 ± *52.6*	104.6 ± *44.3*