AN INVESTIGATION OF BEHAVIOURS WITH ONE HANDED EXERTIONS WITH EXTENDED REACHES

AN INVESTIGATION OF LEANING BEHAVIOURS DURING ONE-HANDED SUBMAXIMAL EXERTIONS WITH EXTENDED REACHES

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ABSTRACT

The purpose of this study was to investigate leaning behaviours when completing tasks with constrained reaches. A logistic regression was developed, with the input of individual subject anthropometry and specific task characteristics, and the resulting model was able to provide a very accurate prediction of when an individual would lean. The inputs to this model give insight into what factors are important in the decision making process when a worker chooses whether lean. The task hand locations with the longest reaches resulted in the most frequent choice to lean. Leaning appears to be particularly common, and important, with long reaching and pulling tasks that can reduce task hand shoulder and trunk loads and improve balance, while allowing the worker to get closer to the task. Leaning hand forces were highest during pulling tasks. These findings are very important to document, as current ergonomic tools neglect to consider that different task characteristics may change how, and when, a worker leans. Even when only the direction of the task hand force was changed, leaning hand forces differed significantly. In this study, leaning hand height was slightly higher for the shoulder height, when compared to the umbilical height, task hand locations. The average height of the leaning hand did not vary considerably and ranged between 106.6cm to 116.3cm, depending on the condition. The leaning hand force magnitude changed as task hand location, force direction and force level changed. Leaning hand forces increased with increasing task hand load. Task hand forces in the push direction were higher compared to push and down exertions, regardless of task hand location or task hand load. The findings from this study are of particular use to industry as ergonomists now have representative forces and heights, to help guide leaning estimates during proactive risk assessments.

DEDICATION

This thesis is dedicated to my parents, Donald and Marilyn Fewster.

Thank you for your love and support. Without you none of this would be possible.

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I would especially like to thank my mom and dad (Marilyn and Donald Fewster). Not only have you been my number on source of funding, but you have always been there for me with countless love and support. I am truly blessed to have parents that have devoted their lives to making my dreams come true.

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Chapter 1 - Introduction

Automotive assembly workers frequently perform one-handed tasks. While completing such tasks, workers often encounter obstructions in the environment. These obstacles can constrain posture, yet they also can provide an opportunity for the worker to use their free hand to help support their body weight. Such tasks will be termed, for my purposes, as "leaning". Specifically, leaning is defined as using the hand, forearm and/or elbow as a means to externally support the body while completing a work-related task. "Bracing" occurs when a part, or parts, of the body other than the upper extremity are used for external support during a work related task.

Without external leaning forces in some situations, postures may be unstable, rendering the task impossible. Automotive assembly workers are often confronted with these types of tasks, including forceful hose installations and the connection of electrical components. Jones et al. (2011) performed a field survey in an automotive assembly plant and determined that, of the one-handed exertion tasks sampled, 53 percent were performed with leaning on the contralateral hand. A second field study by Cappelletto et al (2012) classified and enumerated the distribution of industrial leaning and bracing postures adopted by a large number of workers in an automotive assembly plant. The field study found that, out of the 250 jobs surveyed, 36% demonstrated leaning behaviours (Cappelletto et al. 2012).

Workers may choose to lean to allow for a more effective posture for task completion, or to reduce the loading on the spine (Howard et al. 2012). One handed lifting, with and without leaning, were studied and the results revealed that leaning reduced loading on the spine (Ferguson et al 2002, Kingma & van Dieen 2004). These studies documented that the net lumbar moment and L5/S1 joint forces were about 30% lower, and that compression and shear forces in the lower spine were 15%-17% lower, when leaning (Ferguson et al 2002). In addition to decreasing spinal loading, leaning also has the potential to increase worker capacity by increasing isometric task hand force capacity by up to 31% (Jones et al 2010).

While leaning may have many benefits to the worker, it also poses many problems to ergonomists. Ergonomic assessments of tasks with leaning can be problematic because there is not sufficient data to predict leaning hand forces or the location of the leaning hand. This is especially problematic early in manufacturing design processes, during work simulation, when physical prototypes do not exist. Leaning impacts the joint torques at the shoulder, elbow and down the torso to both ankles which can affect the overall results and decisions from an ergonomic analysis. Unknown leaning forces leaves the estimation of these forces up to the discretion of the analyst. Currently, there is no human digital modeling or posture prediction software that can predict a leaning posture, thus ergonomists must use computer software to manually manipulate a digital model into a presumed leaning position when, in fact, it is predicted that leaning would occur. This requires that assumptions be made regarding how the workers would position themselves in such an environment. It has been shown that a 10-degree error in limiting joint angle can result in ± 30% variations in percent capable strength demand predictions (Chaffin & Erig, 1991). A posture prediction model, that includes leaning postures, would eliminate the need for an analysis to make assumptions about leaning hand force and location and, thus, improve the accuracy and reliability of ergonomic analyses.

Previous studies of push and pull tasks, performed in unconstrained environments where leaning is not available, have documented the effect of variables such as height of force application, distance between body and point of force application and volitional postures on force generation strategies and strength (Martin & Chaffin, 1972; Ayoub & McDaniel, 1974; Chaffin et al., 1983; Kumar, 1991; Gagnon et al., 1992; Granata & Bennett., 2005; Hoffman et al., 2011; La Delfa, 2011). However, the extent to which these principles affect leaning hand force and location is not understood. It is important to study tasks with long reaches because these are the types of tasks workers are often observed performing in automotive assembly plants.

To address some of the questions regarding leaning, the HUMOSIM group conducted some large studies to add to our understanding of the factors that contribute to the postures selected by workers when leaning and bracing surfaces are available. Jones et al (2013) performed a lab study of leaning and bracing with 25 participants. The study consisted of five task-hand force directions (forward, backward, upward, medial and lateral). Three task hand heights; low (43% of stature), medium (59% of stature) and high (76% of stature) and two reaches; close (26% of stature) and far (44% of stature). The study concluded that participants, when permitted to do so, leaned with their hand and brace with their thighs in such a way that increased force-exertion capability. The Jones (2011) thesis includes the full study and Jones et al (2013) includes only a subset from that study (100% of maximum strength conditions, but not 50%), and thus I will refer to the study as Jones (2011) for the remainder of the thesis.

The research of Jones (2011) was the first to document leaning and bracing forces and the postural strategies used when a leaning and/or bracing surface is available. This work added insight to the literature about how workers chose to lean and the force generation strategies associated with leaning. There were several limitations to the conditions tested in Jones (2011). The study only tested medium and close reaches and did not investigate force magnitudes in the down direction. Cappelletto et al. (2012) reported that leaning occurs very frequently during down exertions. This is why it is important that the down force exertion is missing in previous research. There are many more conditions that need to be investigated such as much longer reaches, lower force levels that closer resemble the force levels seen in automotive assembly plants and force exertions in the down directions. Jones (2011) gave participants only one small area to place the leaning hand. Also, they only evaluated hand loads at 50% and

100% of maximum strength and this makes it difficult to understand how leaning changed when task hand requirements change. Each individual participant would have had a different maximum force and thus task hand force levels across participants would not have stayed consistent, making it more difficult to apply the data to actual work environments.

Jones (2011), hypothesized that several different task and subject configuration variables influence leaning hand force and location, including an interaction between; 1) sensitivity of external joint loads (specifically at the low back and task shoulder), 2) task hand parameters such as reach (long and short reaches), 3) height of the task hand, 4) force magnitude, 5) force direction, 6) participant anthropometrics and 7) strength.

Additional information about leaning hand forces and locations will add to our understanding of industrial leaning and help ergonomists make better predictions of how a leaning hand might be used during various industrial tasks. Figure 1 illustrates the novel factors that will be addressed in this current study.

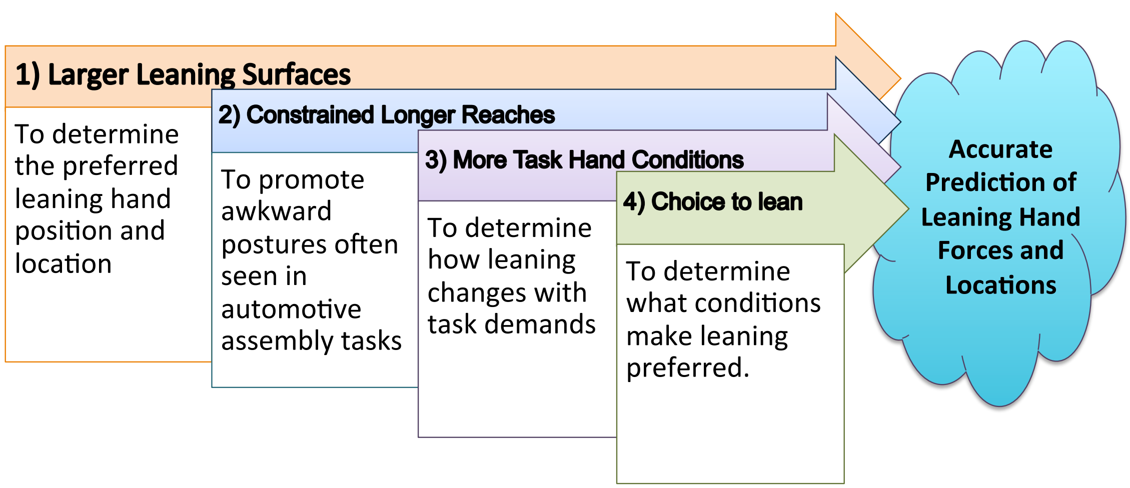

Figure 1: A schematic displaying the future research that is needed to gain a better understanding of how and why workers chose to lean. This study will begin to investigate these factors in an attempt to improve the prediction of leaning hand forces and locations during a particular task.

The purpose of this study was to investigate leaning hand forces and the preferred leaning postures when completing tasks with constrained reaches. The goal of this proposed study was to fill in some gaps, and address some limitations, from the leaning portion of the Jones (2011) study, while allowing more choice and freedom to the participant when leaning. The study has been designed to provide some overlap to the task hand parameters in Jones (2011), however, limitations to that study, and demands from auto manufacturer to improve the work simulation process in proactive ergonomic analyses, have been taken into consideration. This study focused on leaning and constrained reaching to evaluate the more awkward postures often seen in automotive assembly tasks. The results gathered from this investigation will subsequently be available to guide ergonomists on how to account for supportive leaning hand loads during an ergonomic analysis and can be implemented within any ergonomic software package.

Chapter 2: Review of Literature

2.1 Ergonomic tools to address injuries and risk and the limitations when applied to leaning scenarios

In an effort to reduce serious workplace injuries such as tendonitis, epicondylitis, bursitis, tenosynovitis, carpal tunnel syndrome, and thoracic outlet syndrome, researchers have focused numerous studies on correcting well known risk factors such as repetitive motions, forceful exertions and sustained and/or awkward postures. According to Snook (1978), if a job is not acceptable to 75% of the population, a worker is three times more likely to sustain a lower back injury. For this reason, and many others, proactive ergonomics must take into account the acceptable force levels of workers. By having a comprehensive understanding of joint strengths and worker capabilities, more valid decisions can be made about safe workplace designs. Strength measurements and ergonomic tools can then be used in industry to plan safe manufacturing designs to optimize production efficiency while lowering the amount of work days lost to injury. A number of tools have been developed that take into account risk factors such as posture, force and repetition. In general, the functionality of these tools is enhanced by being easy to use, ergonomically valid and adaptable to a variety of tasks. Unfortunately, all of the ergonomic tools currently available are very limited when performing an ergonomic analysis with leaning because there is limited data available regarding how and when workers lean.

The University of Michigan's 3-Dimensional Static Strength Prediction Program (3DSSPP) is one of the most popular and commercially available ergonomics tools used in industry. The main use of the software is to evaluate the demands of various industrial tasks using a biomechanical approach in an attempt to limit and reduce overall risk factors. It is a manikin-based, task analysis tool, which utilizes a statistical model combined with an inverse kinematics algorithm, to calculate numerous outputs, such as spinal compression forces and the percentage capable of the strength requirements, in order to evaluate risk to the worker. This tool can be used to analyze tasks and/or proposed workplace designs prior to the actual construction or reconstruction of the workplace or task. This software uses an approach where the reactive moments at each joint, maintaining the inputted posture and load, are compared to worker population strength from the literature. 3DSSPP will estimate percent capable values, which are the percentage of the population with the strength capacity to generate a moment equal to, or greater than, the resultant moment demand at the joint (LaDelfa, 2011).

Stobbe (1982), compiled a significant portion of the strength data used in 3DSSPP. He developed a series of standardized strength tests that would be best suited to predict 16 functional strengths of various muscle groups in the body based on 7 standardized strength tests, four of which pertained exclusively to the upper extremity. A series of predictive regression models were developed using the inputs of the measured standardized strengths, in order to predict functional muscle group strengths. The standardized strengths that were included were chosen based on how commonly they are used in industrial settings. This tool does not allow for the selection of a leaning hand and, thus, an ergonomic analysis that involves leaning is not possible.

The Siemens Jack software (Siemens, Ann Arbor, MI) is another popular ergonomic assessment tool, with multiple task analysis toolkits. The “Static Strength Prediction (SSP)” and “Force Solver” tools available in Jack are the two toolkits used when looking to predict maximum force capabilities. Like 3DSSPP, the SSP tool predicts the percentage of workers expected to have the static strength necessary to perform a specified task. Unlike 3DSSPP, the Jack software allows for the selection of a leaning hand. The model in Jack is an automated kinematic algorithm to predict leaning hand force exerted at the contralateral hand (Chiang et al. 2006). If the user identifies either hand as a leaning hand, the software will iterate through increasing hand loads applied to the leaning hand until the percent capable threshold is reached (Chiang et al.

2006). The leaning hand force is determined with the task hand load held at 0 N. This force magnitude is then fixed for that hand. A second iteration begins with the task hand, to determine the acceptable task hand force based on the leaning hand force (Figure 2) (Chiang et al 2006). One drawback with this approach is the analysis is based on the assumption that workers will attempt to share the load as much as possible between the joints, and will lean as much as they can until a joint moment limit is reached. This method solves for non-task hand force independently from task hand force and does not consider the postural adjustments that result in response to force generation strategies with leaning available. The approach by Chiang et al. (2006) is also based on the assumption that leaning forces are increased to a magnitude that satisfies the maximum strength capacity of the shoulder

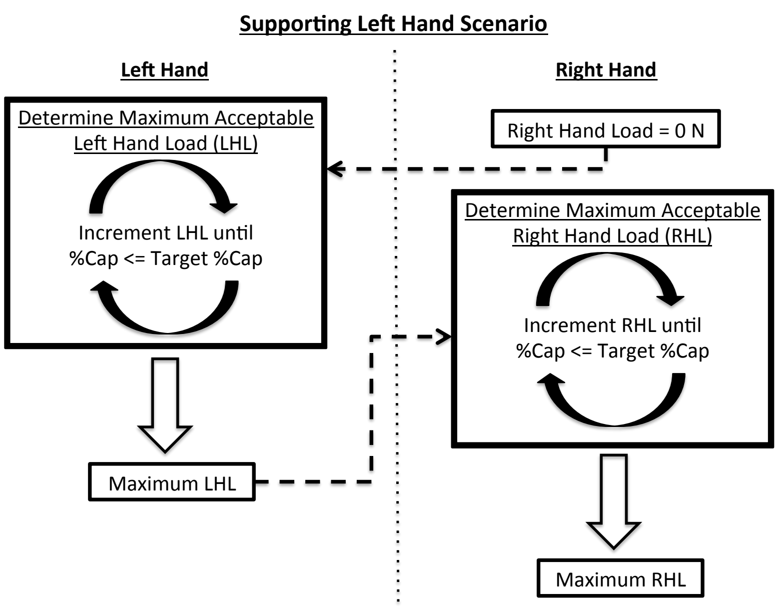

Figure 2: Chiang et al. (2006) software model for a supporting left hand scenario. The supporting (left) hand load is determined first and then used to determine the task (right) hand load. *Figure adapted from Chiang et al. 2006.*

Hoffman (2008) has proposed a separate strength-based, posture prediction model for a wide range of standing hand-force exertions based on empirical and biomechanical data. Hoffman demonstrated that the postures used for one- and two-hand static force exertions tend to maintain shoulder moments at, or below, 37 Nm in 90% of the trials. This did not appear to be affected by hand force direction. In many cases, off-axis forces were observed to minimize the moment arm of the resultant force vector to the shoulder (Hoffman 2008). Trunk twisting moments were also minimized and only increased to a level that was necessary to generate the required force at the task hand and keep shoulder moments below the 37 Nm threshold (Hoffman 2008). The observations by Hoffman (2008) demonstrate that static force exertions tend to maintain shoulder moments below a threshold. This observation is contradictive to the approach by Chiang et al. (2006) that is based on the assumption that leaning forces are increased to a magnitude that satisfies the maximum strength capability of the shoulder.

2.2 Human Digital Modeling and Posture Prediction Approaches

Digital human modeling and posture prediction aim to predict and graphically render human motions during manual tasks based on descriptions of tasks and performers. This technology allows users to place a digital human model (DHM) within a created virtual computer-aided design and manufacturing (CAD/CAM) environment. When developing design prototypes using posture prediction software, designers can utilize human motion simulation to evaluate how their design decisions may affect human motions and thus, postural discomforts, biomechanical stresses, and injury risks during worker-artifact interactions. Such simulations can rapidly identify and rectify ergonomically undesirable and unsafe features in a workplace design. This minimizes the need for costly physical mockups and human participant trials.

The process of developing an accurate posture prediction model is quite difficult because human motion simulation generally does not have a unique solution. The human body almost always has multiple postural options for performing a task (Park et al 2008). It is this deficiency that has resulted in a number of labs around the world to focus their efforts on improving the accuracy of posture prediction.

The Santos group at the University of Iowa, has taken an optimization-based approach to motion and posture prediction. This approach uses a number of human performance measures that serve as the objective functions and constraints that drive cost functions as criteria to define joint postures (Yang et al., 2006). This approach is based on the theory that, depending on what type of task is being completed, human posture is governed by different human performance measures. In general, performance measures are metrics that govern how and why a human model moves, given a particular scenario. Different performance measures can result in different postures. The human performance measures in their model are physics-based metrics, meaning they represent physically significant quantities and are not developed from empirical data (Yang et al., 2006). The perfomance measures are utilized to explain the strategies in which humans may control movements. The problem can be formulated as a single-objective-optimization problem with a single performance measure, or as multi-objective-optimization problem with multiple combined performance measures (Yang et al., 2006). A number of performance measures (i.e. objective functions) have been presented and include: the minimization of joint displacement from neutral, the minimization of effort to attain an end effector location, the minimization of discomfort (leading to movements towards a comfortable position) or the maximization of some performance measure for vision (Abdel-Malek et al, 2006).

The model also includes two primary constraints that drive the cost functions. The first component relates to a 'distance-constraint' and requires that the end-effector (usually the hand) remains in contact with some point in space or trajectory of motion. The second set of constraints represents joint-angle limits, which are dictated by anthropometric data (Yang et al., 2006). While adhering to these constraints and optimization criterion/criteria, an inverse kinematics approach is used to define joint postures for unique tasks. This method is flexible, such that different weighted objective functions can be set for different tasks (Yang et al., 2006).

One major issue with this approach is the lack of validation of the assumptions that are made when the cost and objective functions are set. When using the model, the cost and objective functions are not locked in and the user can change the functions as they feel necessary. The cost and objective functions used to drive posture prediction in this model need to be validated and locked in place. In addition, little evidence has been provided to validate the final predicted postures. The predicted posture may look plausible, however, in reality a worker may perform the task with a completely different posture. An accurate prediction of posture needs to include how an individual performs a task (using empirical data), as well as cost and objective functions. A concrete understanding of how cost and objective functions change with common workplace factors, such as the availability of leaning and/or bracing surfaces, constrained tasks and fatigue throughout the workday, will lead to increased accuracy when predicting posture. The HUMOSIM group at the University of Michigan has taken a data-driven approach to posture prediction. Faraway et al. (1999) was one of the first from the HUMOSIM group to attempt posture prediction and used functional regression to predict reaching motions based on a very large number of experimental trials. In this approach, the regression model was fit to a set of human reaching motion data. Participant anthropometry was used, in addition to hand target location, to predict joint angle time-histories, which were corrected for final hand position based on inverse kinematic techniques (Faraway et al, 1999).

Zhang & Chaffin (2000) developed a dynamic, three-dimensional optimization-based differential inverse kinematics (ODIK) model. The general principle of this model is that weighting parameters are used for individual segments to quantify their contributions to an instantaneous posture change. These movement specific parameters are estimated through optimization procedures, such that the reproduced profiles best fit the observations (Zhang & Chaffin, 2000). Overall, the ODIK model offered a computationally effective modeling method with very good prediction accuracy at close reaching ranges and the majority of the movements used in the model development were fitted with small errors. However, the application of the model to more extreme reaches resulted in large prediction errors.

Despite the advances in posture prediction, Park et al. (2008) states that the existing models are "*limited in that they lack some basic capabilities required for simulating the variety of human motions seen in common manual tasks*". The three main limitations identified were; 1) universality; the lack of a single unified model for simulating categorically different motions. The existing simulation models are limited to simulating only a single specific motion category and appear to be unsuitable for handling multiple motion categories. 2) learning; most current simulation models lack the ability to learn new motion behaviours. Real humans continually learn new motion behaviours by observations and practices. 3) variability; modeling variability allows the designers to visualize the consequences of many likely techniques, but most models have not accounted for this.

To address these limitations, Park et al (2008) developed the memory-based motion simulation (MBMS) model. This model starts with a motion database to provide the task space for general motions (termed "root motions") and relies completely on the development on an empirical database. The model utilizes real human motion samples recorded in motion capture experiments as templates for simulating novel motions and, thus, predicts the postures a given person would get into given specific input criteria (Park et al 2008). The MBMS model is comprised of four basic components: 1) the motion database, 2) the root motion finder, 3) the motion variability analyzer and 4) the motion modification algorithm (MoM) (Park et al 2008). A motion simulation derived from the MBMS model begins with a submission of an input scenario. The input can be described in terms of the following: motion category (reach, lift/lowering, carrying etc.), initial conditions (initial posture, initial hand location, initial load position etc.), hand load weights or required hand forces, and motion task goals (final hand position, final load position etc) (Park et al 2008). The motion performer is described in terms of personal attributes, such as age, gender, height, and weight.

Once a given input simulation is submitted, the root motion finder searches the motion database to find and retrieve the motion samples that closely matches the input simulation scenario (Park et al 2008). The motion database functions as a “memory” of human motor skills. Each recorded motion is stored in the form of multiple joint angle-time trajectories and joint center position-time trajectories. The motions retrieved by the root motion finder are called root motions. The root motions then serve as approximate templates for simulating motions for a given input scenario (Park et al 2008). Given that none of these root motions are likely to match the task exactly, a motion modification algorithm (MoM algorithm) is then used to adapt them to the task, while minimizing the deviations from the original joint trajectories (Park et al 2008).

Despite the strengths, there are considerable limitations to this model; the current MoM algorithm does not provide a general and robust method for incorporating various constraints defined in the task space. The initial posture modification and the in-between trajectory modification are performed in the joint-angle time domain without considering any task space constraints, other than the new hand position/orientation constraints (Park et al 2008). The empirical data used to predict the postures in this model are motions recorded under non-leaning conditions. The current model is not able to simulate human obstruction avoidance behaviors and or leaning/bracing behaviours during goal-directed motions (Park et al 2008). The limitations within this model are mainly because the motions recorded do not incorporate leaning and/or constrained movements and, therefore, it is not possible to perform an ergonomic analysis that involves leaning with this model.

Recently, the HUMOSIM group has conducted some large studies to add to our understanding of the factors that contribute to the postures adopted by workers. As previously mentioned, Hoffman (2008) manipulated hand force direction, location and magnitude for 10 male and 10 female standing participants and determined their effects on whole-body posture. Isometric forces were applied at four relative magnitudes (25%, 50%, 75% and 100% of maximum), at three heights (thigh, elbow, overhead) with one or two hands in four directions (anterior, posterior, up and down) (Hoffman 2008). From this study, posture prediction models were developed. A biomechanical approach to posture prediction was chosen so that the predicative capability of the model would not be limited to a specific data set but instead, be applicable to a wide range of high-force standing exertions (Hoffman 2008). Predictions are driven by sensitivity to external shoulder loads and static balance requirements, and the constraints of upper and lower extremity kinematics. The process of developing the posture prediction models involved the input of task parameters (task hand(s), required hand force and hand height) and worker characteristics (gender, stature and body mass) (Hoffman 2008).

The model was constrained by parameters from empirical data. The principle findings from the laboratory data were used as constraints in the model development (Hoffman 2008). These constrains included:

1) To maintain shoulder moment within an acceptable range: a) People exert substantial off-axis forces, producing higher than required load magnitudes, but direct the force vector towards the shoulder and b) People orientate the torso to place the shoulders closer to the hand force vector (Hoffman 2008).

2) The position and length of the base of support changes with hand force magnitude and direction (Hoffman 2008).

The posture prediction algorithms are comprised of a series of steps that define key aspects of posture. The following steps are included in the posture prediction process; 1) compute the hand force vector and plane 2) predict elbow angle 3) position the shoulder with respect to the force vector to maintain shoulder moments below 20 Nm, 4) set the torso angle, 5) compute the foot placement, 6) set shoulder angle, 7) determine location of the pelvis and, 8) compute pelvis orientation (Hoffman 2008).

The algorithms developed performed well in the push and pull direction, but a number of different strategies were used when performing up and down efforts and this limited the performance of the model. This work has provided valuable insight into the effect of load demand magnitude, direction and height on the postures adopted, so that these postural strategies can be accurately predicted. However, one of the limitations of this work is that there were no restrictions on how close participants could get to the force handle. The influence of obstructions in the environment that would change postures (such as leaning on an obstruction) and force generation strategies was not considered. This is a considerable limitation, as it is common that a worker is restricted in how close they can get to a task. Obstructions and kinematic constraints within a task configuration may limit the postures that can be achieved and generate more realistic postures seen in the workplace.

2.3 Leaning in the Workplace

The first survey to investigate leaning and bracing behaviours was conducted by Jones et al. (2008) in an automotive assembly plant to obtain an initial understanding of leaning and bracing behaviours to qualitatively determine how workers support themselves. Of all the tasks examined, 48 percent were performed with some element of leaning or bracing. Jones et al. (2010) determined that, of the one-handed exertion tasks sampled, 53 percent were performed with leaning. It was concluded that tasks involving forceful exertions, while standing in a restricted environment, are common in the automotive industry and workers frequently leaned on obstacles in the environment.

Cappelletto et al (2012) performed a second field survey in Ford Motor

Company's Oakville Assembly Plant. The objective of that research was to determine when, where and how workers lean or brace, and then use the information to guide future laboratory studies that resemble tasks workers are commonly observed leaning and/or bracing. The survey was created in response to auto manufacturer's need to improve their ability to predict leaning and bracing behaviours during the work simulation process used in proactive ergonomic analyses.

The field study classified and enumerated the distribution of industrial leaning and bracing behaviours adopted by a large number of workers performing automotive assembly tasks. In total, 250 jobs were observed and 101 (41%) exhibited at least one task element in which the workers adopted leaning and/or bracing behaviours and 90 of these jobs contained at least one task element with only leaning (36%) (Figure 3). There were a total of 613 task elements in the 101 jobs observed with leaning and/or bracing and, of this, 363 (59%) elements were identified as having leaning and/or bracing. Out of the entire task elements that had some element of leaning and/or bracing (363), the worker was leaning without bracing in 57% of the tasks (Figure 4).

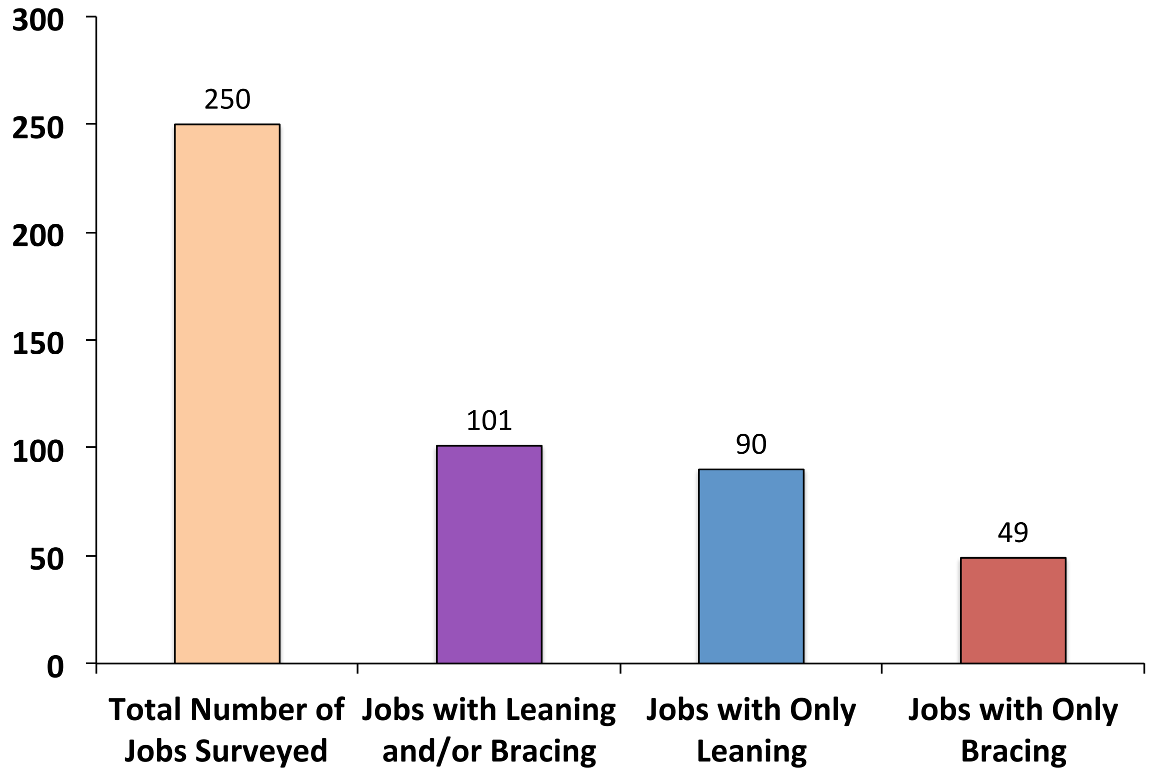

Figure 3: The total number of jobs included in the survey, as well as the total number of jobs with leaning and/or bracing elements. As a percentage of the total jobs surveyed, 36% had at least one element with leaning (Cappelletto et al. 2012).

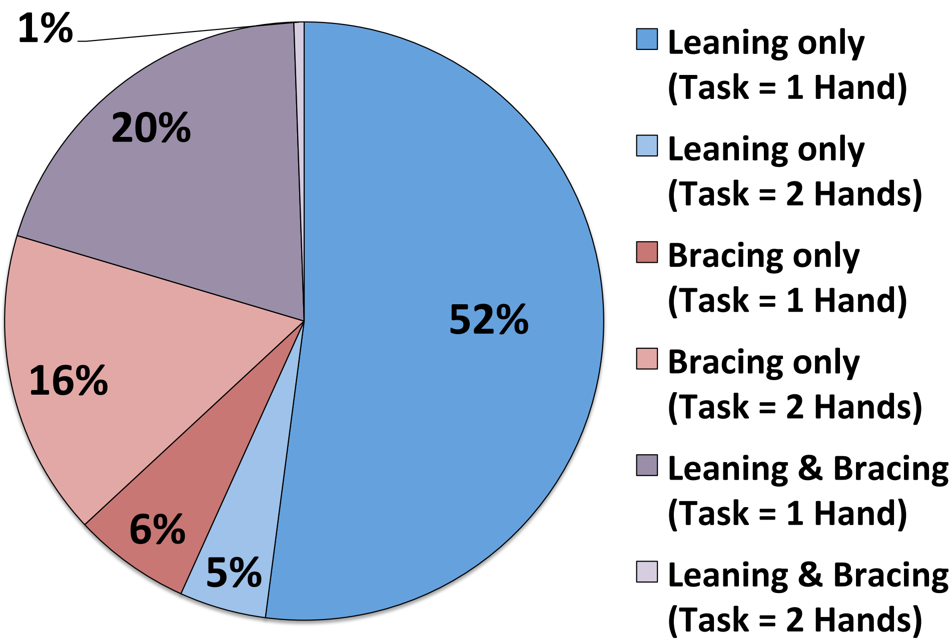

Figure 4: The task elements that contained leaning and/or bracing (363), broken down by the type of external support and the number of task hands used, for the jobs with observed leaning and/or bracing. The blue portion of the pie chart represents leaning only (57%), the red portions represent bracing only (22%), and the purple portions represent a combination of both leaning and bracing (21%). Task = 1 Hand indicates that only one hand was used to complete the task element. Task = 2 Hands indicates that both hands were needed to complete the task element (Cappelletto et al. 2012).

Leaning was the most common method of external support when the worker was using only one task hand (either right or left). The most common height at which leaning occurred was approximately 1.52 meters. This would be at about eye level for an average female employee. The survey determined that leaning occurs most frequently at task hand heights at, or above, shoulder (Cappelletto et al. 2012).

2.4 Leaning

The previous two surveys conducted by Jones et al. (2010) and Cappelletto et al. (2012) confirmed the prevalence of tasks involving leaning behaviors. It is likely that leaning is prevalent during labor-intensive tasks common in automotive assembly plants to help stabilize a worker's body while exerting a force. In addition, leaning also increases capacity, and has been shown to increase isometric task hand force by up to 31% (Jones et al 2010). Aside from increasing capacity, leaning can also help the worker adopt a more comfortable position while performing a task, change the task demands, or to reduce joint loading (Godin et al 2008). Leaning reduces spinal compression and shear during one handed lifting tasks (Ferguson et al 2002). Kingma and van Dieen (2004) found that the net lumbar moment and L5/S1 joint forces were about 30% lower for lifts that involved leaning on the free hand compared to lifting without leaning.

Lardi and Frazer (2003) determined that the magnitude of force exerted at the leaning hand, ranged from 10% to 15% of body weight. The magnitude of the leaning hand force was directly proportional to the amount of trunk flexion (Lardi & Frazer, 2003). In all trials, L4-L5 compression estimates were significantly lower during one-handed tasks when leaning (Lardi & Frazer, 2003). For the purpose of determining if assembly workers use consistent leaning hand forces, Godin et al. (2006) evaluated forces exerted at a prescribed leaning location, as a percentage of body mass. The assembly tasks chosen were a small subset of one-handed tasks commonly seen in the automotive industry and were physically re-created in a laboratory environment. Hand leaning forces ranged from 5.5 to 12.1% of body mass for the various tasks (Godin et al 2006). While the results from that study are directly applicable to a small subset of common assembly tasks, it was the first study to quantify supportive leaning forces for specific auto assembly tasks.

Jones (2011) performed a lab study of leaning and bracing with 25 participants. The study consisted of five task-hand force directions; forward, backward, upward, and lateral forces to the right and left. Three task hand heights were studied, low (43% of stature), medium (59% of stature) and high (76% of stature) and two reaches close (26% of stature) and far (44% of stature). A leaning handrail was set to hip height (55% of stature) and the top edge of the thigh-bracing surface was located at upper leg height (52% of stature). The position and orientation of the leaning surface was manipulated independently; there were two locations of the leaning surface, close (5% of stature), far (22% of stature) (Figure 5). Four conditions were tested: 1) no leaning or bracing, 2) leaning allowed but no bracing, 3) bracing allowed but no leaning, 4) leaning and bracing allowed. All force exertions were performed at 50% and 100% of maximal force (Jones 2011).

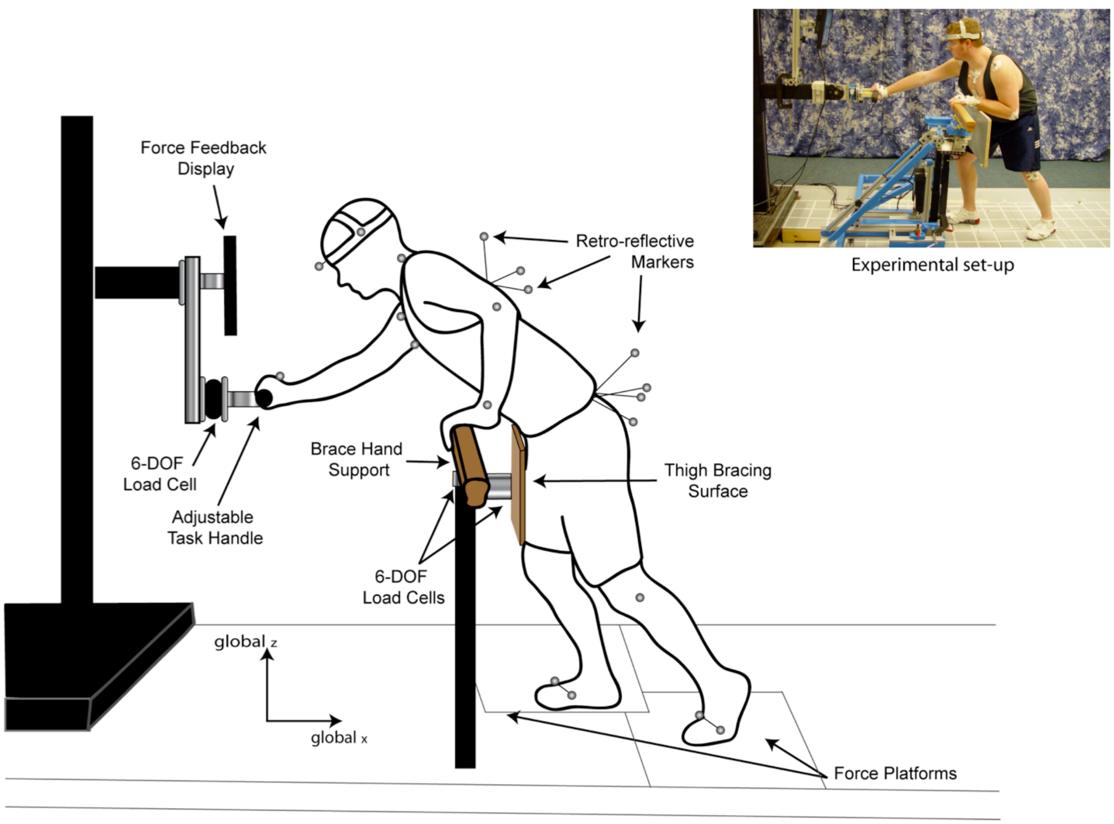

Figure 5: Laboratory setup of the Jones (2011) leaning and bracing study. Notice the thigh bracing surface with a 6-DOF force plate along with the "brace hand support" used for leaning (Jones, 2011)

Leaning and bracing were both found to increase maximal pulling forces. Substantial off-axis forces were observed and, most importantly, the magnitude and direction of task hand changed with varying levels of leaning and bracing availability (Jones 2011). The study concluded that, when participants are permitted to do so, they will lean with their hands and brace with their thigh in such a way that increases force-exertion capability. When a task hand exertion is performed in the absence of leaning or bracing availability, the exertion is derived from body and ground reaction forces alone. When leaning, oppositional forces are generated at both the leaning hand and the leaning surface, this enables an increase in resultant task hand force magnitude and off-axis forces (Jones 2011). Leaning and/or bracing was also found to significantly change the direction of task hand forces for a wide range of force directions and handle locations (Jones 2011).

The work of Jones (2011) was the first to document leaning and bracing forces and the postural strategies used when a leaning and/or bracing surface is available. This work added insight to the literature about how workers chose to lean and the force generation strategies associated with leaning. However, more work needs to be done in order to accurately predict the leaning hand locations and forces associated with a task.

Chapter 3 - Methods

3.1 Participants

Twenty healthy female participants, with ages ranging from 18-30 years, (age 23.8 ± 2.6, mass 60.6 ± 7.6 kg, height 165.3 ± 8.3 cm, arm length 72.6 ± 4.8 cm, shoulder width 29.3 ± 2.6 cm, shoulder height 138.9 ± 7.2 cm, umbilicus height 101.0 ± 5.9 cm) were recruited. A table with each individual participant's anthropometrics and strength is provided in Appendix A. All participants were right hand dominant and asymptomatic of any musculoskeletal disorders for the preceding 12 months. The study was reviewed and approved by the McMaster University Research Ethics Board. Prior to the beginning of the experimental protocol, participants were informed of the purpose, methods, and testing protocol of this study and signed a written consent form (Appendix B). Anthropometric measurements were recorded prior to the commencement of the experimental protocol (details provided below).

3.2 Instrumentation and Data Acquisition

A tri-axial load cell (100 lb 6-axis transducer, Advanced Mechanical Technology Inc., Watertown, MA) was used to measure the force exerted by the task hand. A vertically orientated padded handle was attached to a custom built steel apparatus. The apparatus could be adjusted vertically, horizontally, anteriorly and posteriorly to control for the location of the handle. An additional tri-axial force plate (Advanced Mechanical Technology, Inc.) was used to measure the force at the leaning hand. A large metal plate (18.5 x 30 cm) was placed over the force plate. A wooden horizontal surface (18.5 x 9.75 cm) was then attached to the medal plate this provided subjects with a leaning surface and was affixed to the surface of a vertically oriented force plate. The force plate was attached to vertical lengths of 80/20 rail using a series of nuts and bolts, allowing adjustments for leaning location to be made in the vertical direction. All force data were collected at 400 Hz with custom LabView software and converted by a 12-bit A/D converter. The force transducer's voltage output was calibrated to Newtons.

Kinematic data were recorded at a sample rate of 60 Hz using eleven cameras (Raptor-4. Motion Analysis Corporation, Santa Rosa, CA) and motion capture software (Cortex 1.3.0, Motion Analysis Corporation, Santa Rosa, CA). Fifty-two markers were placed on each participant. A list of the marker setup is available in Appendix C and a figure of the marker placement is available in Figure 6.

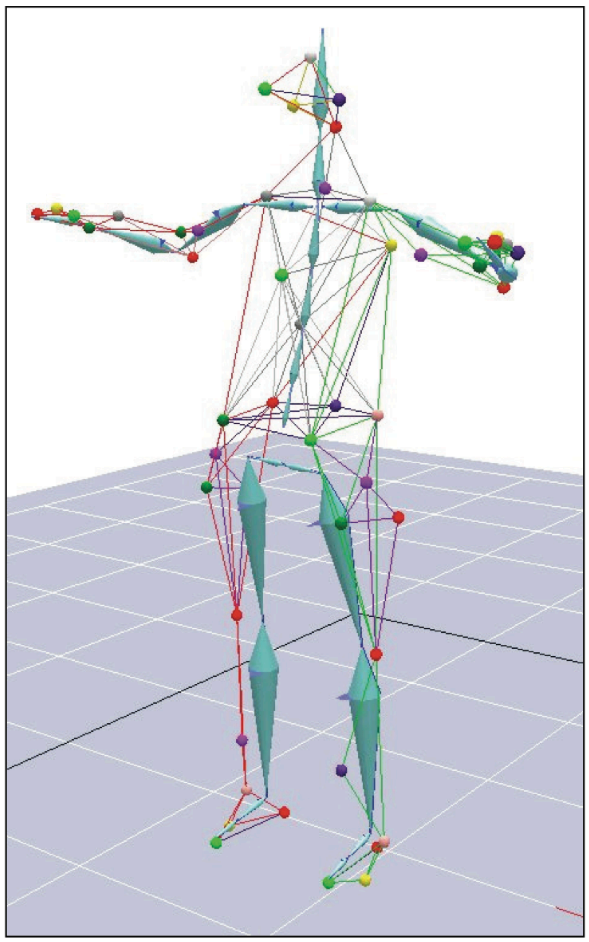

Figure 6: Pictorial representation of the full body marker placement

3.3 Experimental Protocol

3.3.1 Anthropometric Measurements

Anthropometric measurements of height (cm), weight (kg), maximum arm length (cm), shoulder width (cm), shoulder height (cm) and umbilicus height (cm) were taken. The anthropometrics were defined using the following conventions:

1. Arm length was the distance from the acromion process of the scapula to the 3rd metacarpophalangeal (MCP) joint
2. Shoulder width was the distance from the left acromion process to the right acromion process
3. Shoulder height was measured from the acromion process to the ground.

3.3.2 Strength Testing

Static shoulder, elbow and low back strength were tested as potential inputs to a logistic regression to predict when a leaning strategy would be used (see details later). This was completed with a standardized strength testing protocol, using the Biodex isokinetic dynamometer (Biodex 4, Bidoex Shirley, NY). Maximal isometric exertions in flexion and extension, abduction and adduction, were measured to determine shoulder strength using the Biodex shoulder strength attachment. Flexion-extension exertions were performed at 60 degrees of scapula elevation in the sagittal plane (Figure 7) and the abduction-adduction exertion were performed at 60 degrees of scapula elevation in the frontal plane (Figure 8). Elbow strength was tested with a maximal flexion and extension protocol using the Biodex elbow flexion/extension attachment (Figure 9). Flexion-extension exertions were performed with the elbow flexed at 90 degrees. Maximal seated lumbar flexion and extension strengths were collected using the Biodex dual position trunk flexion/extension attachment. Trunk flexion-extension exertions were performed with the participant seated with the hips flexed and the trunk extended to 60 degrees of elevation. Each strength test was repeated twice, and the higher of the two measures was taken as the final value. Two minutes of rest was given between exertions to minimize the effects of fatigue.

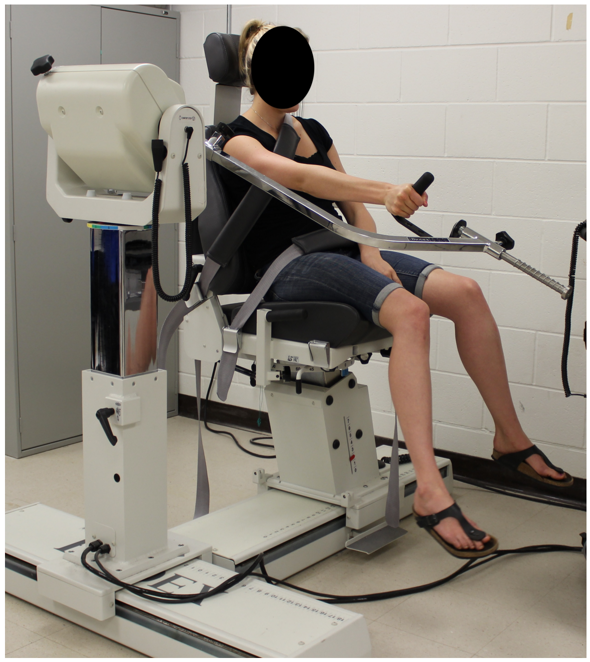

Figure 7: Example of the shoulder flexion-extension strength testing. The right shoulder angle was set and held at 60 degrees of elevation, in the frontal plane, with the elbow fully extended. The participant then applied maximal isometric force exertions while pulling up on the handle (flexion) and then pulling down on the handle (extension).

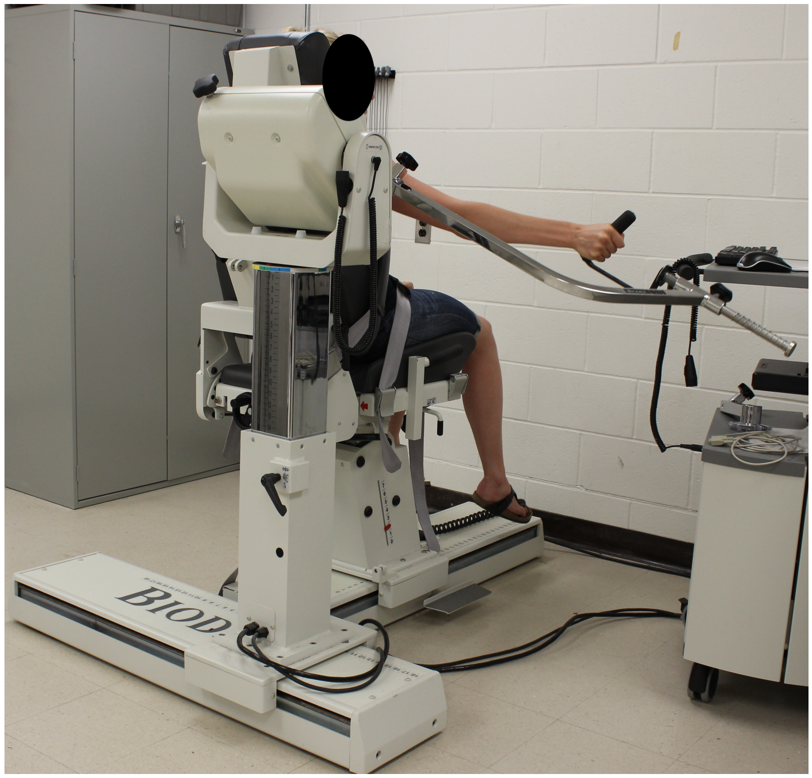

Figure 8: Example of the shoulder abduction-adduction strength testing. The right shoulder angle was set and held at 60 degrees of elevation, in the sagittal plane, with the elbow fully extended. The participant then applied maximal isometric force exertions while pulling up on the handle (abduction) and then pulling down on the handle (adduction).

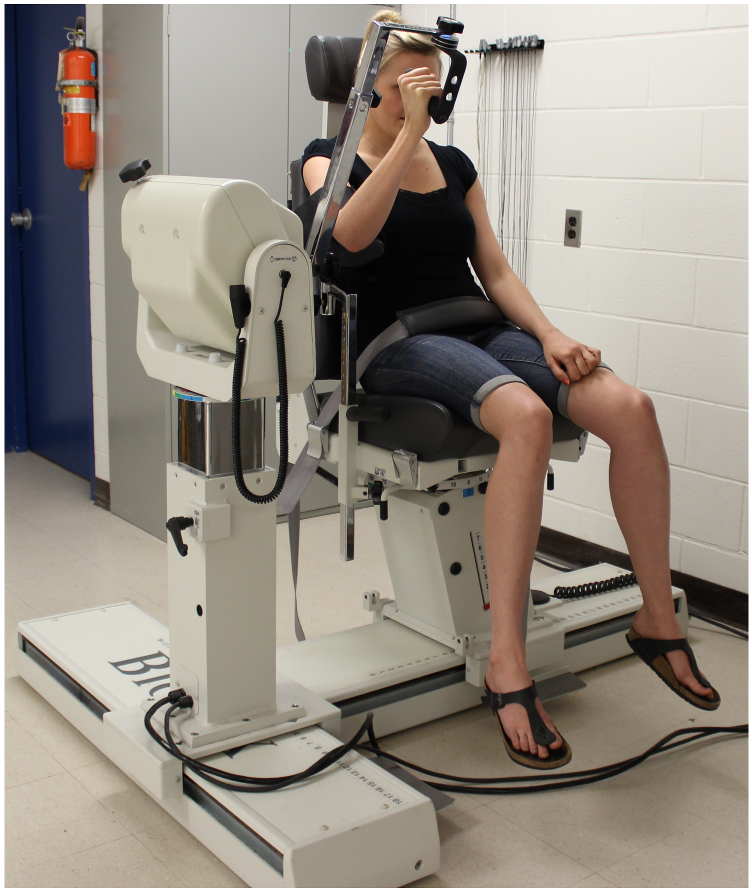

Figure 9: Example of the elbow flexion-extension strength testing. The right elbow angle was set and held at 90 degrees of flexion. The participant then applied maximal force exertions while pulling up on the handle (flexion) and then pulling down on the handle (extension).

3.3.3 Task Familiarization Protocol

Participants were taken through a familiarization protocol, in which they were required to produce force in one of the four pre-selected task hand locations. During the familiarization protocol, participants were encouraged to explore different postural strategies with and without the aide of the leaning surfaces. These practice trials served as an opportunity for participants to identify their preferred postures (with or without the leaning surface) and gain familiarity with the force feedback sound that played once the required force level had been reached. Participants practiced performing exertions with all combinations of the two force magnitudes (high and low) and three directions (push, pull and down).

3.3.4 Experimental Trials

Four task hand locations were used for the experimental trial data collection. The locations were defined by a combination of horizontal (H) and vertical (V) locations. The two vertical task hand locations were at shoulder height (high) and umbilical height (low). The two vertical hand locations were 95% (short) and 120% (long) of arm length based on the anthropometric measurements. This resulted in a total of four hand locations (low-short, low-long, high-short and high-long). Participants were constrained to stand on or behind a line drawn on the floor to control the minimum horizontal reach distance from the feet to the handle (Figure 10). At each task hand location, participants performed all combinations of two force exertions (27.5 and 55 N) in three directions (push, pull and down), for a total of 24 conditions.

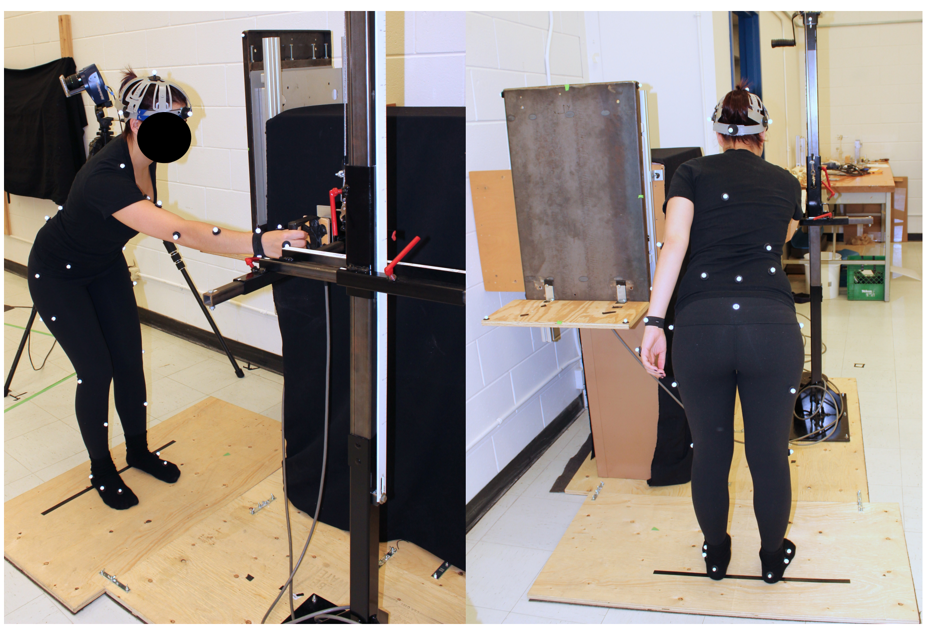

Figure 10: An example of the experimental setup during a long reach condition. Participants were instructed to stand with their ankles over the black line drawn on the floor. This was done to constrain the distance between the participant and the task handle. The task handle horizontal distance was adjusted such that the

reach distance was calculated from the center of the black line to the center of the handle. The subject grasped the handle, attached to a tri-axial load cell, with their right (dominant) hand.

Each of these 24 task conditions above were performed twice, once with the availability of a leaning surface and once without the availability of a leaning surface (Table 1). This study used a randomized block design. Testing randomization was blocked by hand location (n=4) and then direction and force presentation order was randomized within each hand location. A large vertical surface attached to a horizontal leaning surface was available during the leaning conditions. This surface allowed ample space for the participant to lean in any desired posture (Figure 11). The bottom of the horizontal leaning surface was set at 10 cm above wrist height. During the initial 24 conditions participants were not instructed what the leaning surface was available for. Participants were asked to complete the task in such a way that it was most comfortable for them. During each condition, their choice to use or not use the leaning surface was documented. At the end of the testing protocol; 1) the trials in which the participant chose not to lean were repeated, requiring the participant to use the leaning surface and 2) the trials where the subject chose to lean were repeated requiring the participant not to lean. Participants were not be aware of the additional conditions so that it did not affect their choice of whether to lean during the original 24 trials.

In total, 48 exertions were completed during the study (4 locations x 2 force magnitudes x 3 exertion directions x 2 leaning conditions). In order to complete these exertions with adequate rest between trials, along with strength testing and a familiarization protocol, the entire study took place over two sessions. One session was 45 minutes long and consisted of strength testing. The second session was 1.5 hours and consisted of the 48 exertions. A minimum of two days rest was given between sessions.

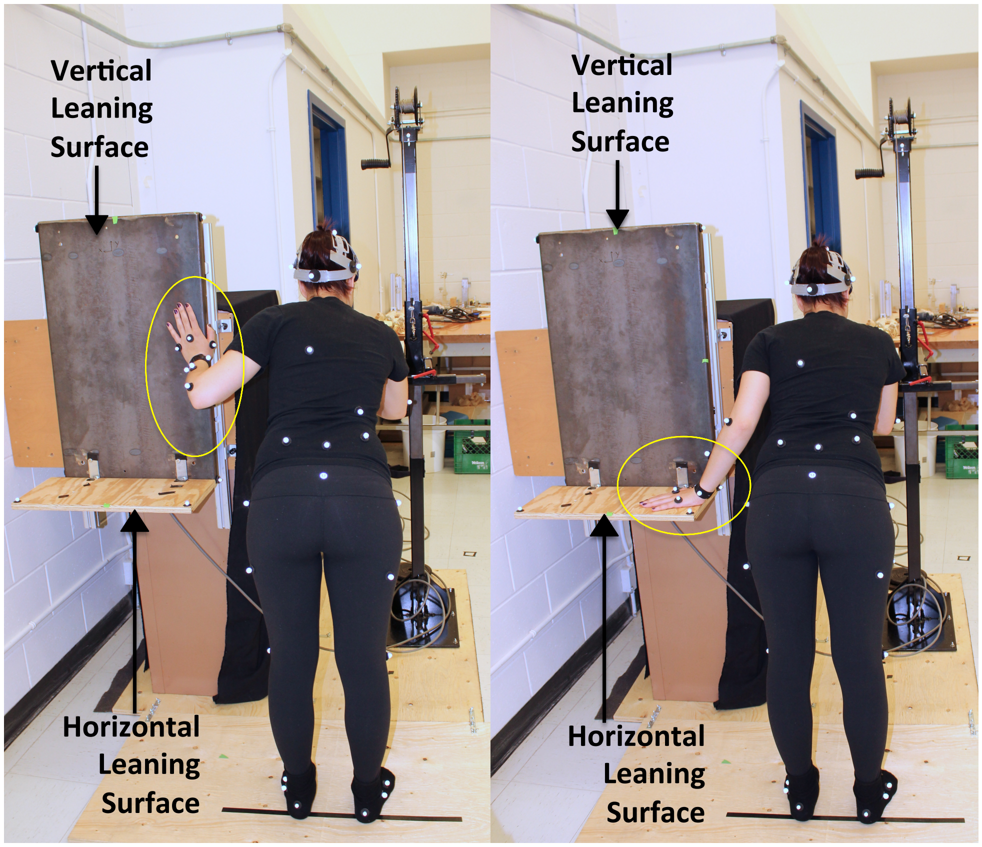

Figure 11: An example of a long-reach condition with a lean. Participants could use either the vertical or horizontal surfaces to help support themselves during the exertions. The bottom of the horizontal leaning surface was placed 10 cm above standing wrist height. The vertical leaning surface was mounted to a tri-axial force plate to measure the leaning forces.

Table 1: A matrix showing a combination of the leaning conditions in the Jones (2011) study and the conditions that were studied in this investigation.

		No Bracing											
Task Hand Height	Task Hand Reach	**No Leaning**						Leaning					
		Push	Pull	Right	Left	Up	Dwn	Push	Pull	Right	Left	Up	Dwn
High: 75-85% of Stature	Close: 60% arm reach	J	J	J	J			J	J	J	J		
	Medium: 90% arm reach	F	F				F	F	F				F
	Far: 100% -110% arm reach	F	F				F	F	F				F
Medium: 60% of Stature	Close: 60% arm reach	J	J	J	J	J		J	J	J	J	J	
	Medium: 90% arm reach	F	F				F	F	F				F
	Far: 100% -110% arm reach	B	B	J	J	J	F	J	J	J	J	J	
Low Jones 43% of stature	Close: 60% arm reach	J	J	J	J	J		J	J	J	J	J	

J	Jones Study
F	Fewster Study
B	Both Studies

3.4 Data Analysis

For each exertion, the posture and leaning hand forces were recorded for the sample immediately following the first task hand force value that exceeded the desired force level (27.5 or 55 Newtons). This will be termed the “task frame”. Participants were required to have the task hand force in the intended direction be at least 90% of the resultant task hand force. In cases where this was not the case, the exertion was repeated. The motion capture data were streamed into the Jack 7.1 software (Siemens, Michigan) for data processing (Figure 12). The task frame was matched to the motion analysis data and it was this frame that was used and streamed into Jack. This allowed for joint angles and moments to be calculated during each trial and to be synced to the force data.

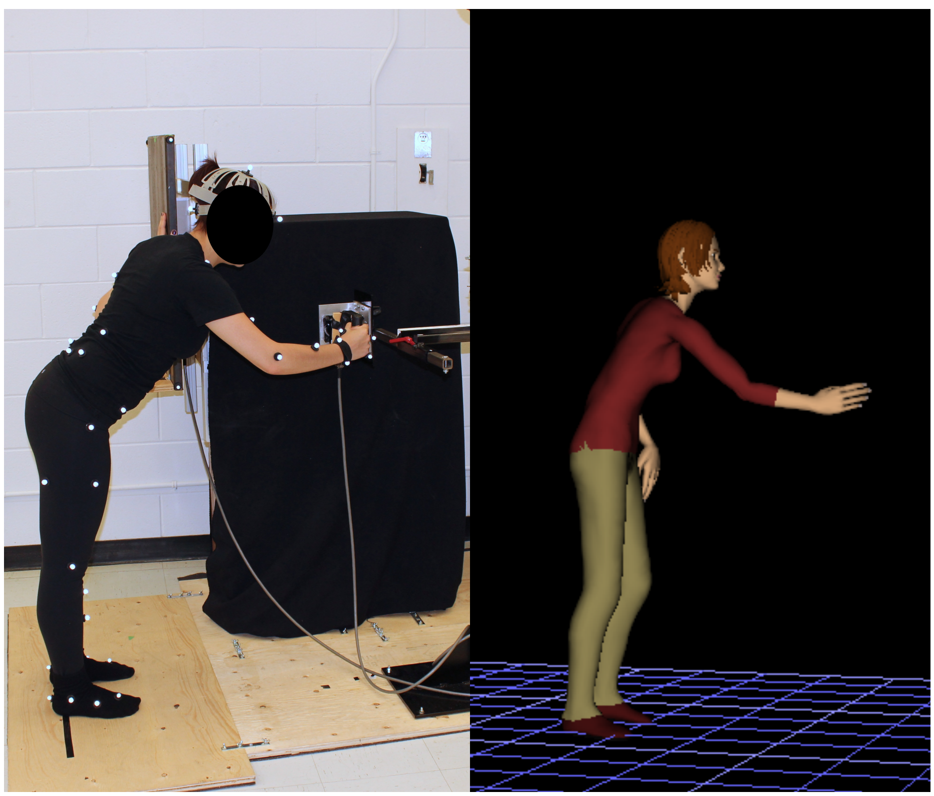

Figure 12: A representation of a participant completing one of the study conditions and the associated Jill mannequin.

The postures adopted by all joints and forces were quantified using the Jack Force Solver. For the task hand, the resultant force vector was assumed to be either 27.5 or 55 Newtons in the desired direction. For the leaning trials, the resultant leaning hand force and associated three unit force vectors were inputted into the Jack software’s Force Solver for the left hand. The following kinetic and kinematic variables were outputted and analyzed: right (task) and left (lean) elbow flexion angle, right and left elbow flexion moment, right and left resultant shoulder angle (this angle was calculated using only the vertical and horizontal shoulder angles, and the humeral rotation angle was omitted to give a better representation of the deviation of the humerus from the neutral posture), right and left resultant shoulder moment (using all three shoulder moments), trunk flexion angle and resultant trunk moment. Resultant leaning hand force and leaning height were also calculated for only the trials that included leaning. The location of the leaning hand (x, y, z coordinates) was determined from the motion analysis data using the location of the left hand knuckle marker.

3.5 Statistical Analysis

The statistical analysis was split into three sections. Each section focused on answering questions regarding leaning.

3.5.1 Effects of Leaning on Trunk and Task Hand Posture and Joint Loading

A 4-way repeated measures ANOVA was performed to determine the effects of the following independent variables; task hand location (high-long, high-short, low-long and low-short), task hand force (27.5 N and 55 N), task hand force direction (push, pull and down) and leaning condition (lean and no lean). The following dependent variables were analyzed: resultant trunk moment, trunk flexion angle, resultant shoulder moment of the task arm, resultant shoulder angle of the task arm, elbow moment of the task arm and elbow flexion angle of the task arm. The focus of this analysis was on main or interaction effects that included the effects of the leaning conditions.

3.5.2 Effects of Leaning on Leaning Arm Posture and Joint Loading

A 4x3x2 repeated measures ANOVA was performed to determine the effects of the independent variables; task hand location, task hand force, and task hand force direction on the leaning arm. This analysis included only the 24 exertions with leaning. The following dependent variables were analyzed for the leaning arm: resultant shoulder moment, resultant shoulder angle, elbow moment and elbow flexion angle, in addition to resultant leaning hand force, leaning hand height, and the percentage of participants who chose to lean for each condition.

3.5.3 Predicting the Choice to Lean or Not Lean Based on Task Conditions

The third goal of this study was to develop a logistic regression function with the 20 participants to determine what variables play a significant role in determining when and why an individual chooses to lean. This function was used to predict if an individual would choose to lean in response to particular task conditions. The independent variables that went into this function were participant shoulder flexion-extension strength, and abduction-adduction strength, elbow flexion-extension strength, trunk flexion-extension strength, task hand force, participant arm length and stature, mass, direction of force exertion, task hand height as a percentage of stature, task hand reach as a percentage of arm length. Based on the choice that each participant made during the first 24 exertions, they were coded as a 0 for choosing not to lean and 1 when a lean was freely selected. A logistic regression function was developed to predict whether a participant would chose to lean or not lean during any given condition within this investigation. Predicted values that were <0.5 were assumed to be 0 (no lean) and any value ≥0.5 were assumed to be 1 (lean).

Chapter 4 – Results

For the sake of this thesis, only the main effects of leaning, or interactions involving leaning will be presented. The loads, directions and locations were mainly in place to see if they would affect leaning. This thesis will present the main and interaction effects where $p<0.05$ and the omega squared value is greater than 1% (Table 2). For each independent variable, only the highest order significant effect will be presented.

Table 2: Summary of p values for each ANOVA. The independent variables in grey are the variables that did not involve leaning. The p values in red are the variables that will be reported (highest order significant effect with an omega squared value greater than 1%). The top table presents the findings from the 4-way ANOVAs. The bottom table indicates findings for the leaning arm based on the 3-way ANOVAs.

Effect	Resultant Trunk Moment	Trunk Flexion Angle	Task Arm			
			Resultant Shoulder Moment	Elbow Flx/Ext Moment	Elbow Flexion Angle	Resultant Shoulder Angle
Lean	0.0040	0.7040	**0.0001**	0.3230	**0.0001**	0.0200
Location (L)	0.0001	0.0001	0.0001	0.1700	0.0001	0.0001
Direction (D)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Force (F)	0.0670	0.2980	0.0001	0.0001	0.0001	0.0140
Lean x L	0.0001	0.3120	0.2370	0.8110	0.5620	**0.0060**
Lean x D	0.0080	**0.0360**	0.4280	**0.0370**	0.2410	0.5710
L x D	0.0110	0.0410	0.0001	0.6020	0.1070	0.0040
Lean x F	0.0001	0.3840	0.6680	0.3100	0.7440	0.1400
L x F	0.0001	0.4980	0.0001	0.0001	0.1260	0.0460
D x F	0.0001	0.0250	0.0001	0.0001	0.0001	0.0290
Lean x L x D	0.0590	0.7010	0.3890	0.2710	0.4430	0.1410
Lean x L x F	**0.0120**	0.3810	0.7570	0.9920	0.1310	0.3820
Lean x D x F	0.1140	0.5500	0.8270	0.4840	0.9440	0.1850
L x D x F	0.0001	0.9790	0.0001	0.0001	0.4480	0.4510
Lean x L x D x I	0.4020	0.5400	0.6130	0.8830	0.9280	0.5750

Effect	Leaning Arm					
	Resultant Force	Hand Height	Resultant Shoulder Moment	Elbow Flx/Ext Moment	Elbow Flexion Angle	Resultant Shoulder Angle
Location (L)	0.0001	**0.0080**	0.0001	0.0410	**0.0001**	**0.0030**
Direction (D)	0.0001	0.1100	0.0001	0.0001	**0.0380**	**0.0001**
Force (F)	0.0001	0.6820	0.0010	0.0160	**0.0010**	0.8840
L x D	**0.0001**	0.8110	**0.0001**	**0.0340**	0.3200	0.5850
L x F	0.0590	0.5220	0.5030	0.2540	0.6510	0.1730
D x F	**0.0001**	0.2580	**0.0001**	**0.0001**	0.2990	0.3020
L x D x F	0.3230	0.3150	0.7900	0.9950	0.4660	0.9510

4.1 Choice to Lean and Logistic Regression Results

There was a Location main effect for the percentage of participants that chose to lean ($p<0.05$). The two long reaches used leaning an average of 31.5% of the time, which was significantly higher than the two short reaches with an average of 15.5%. Both long reaches had a significantly higher percentage of choice to lean than the short reaches. There were no differences between the two long reaching task hand locations or the two short reaching task hand locations (Figure 13). Significantly more participants chose to lean at the High-Long task hand location when compared to the High-Short and Low-Short locations (Figure 13). In addition significantly more participants chose to lean at the Low-Long location than at the Low-Short task hand location and High-Short task hand location.(Figure 13). There was no significant difference in frequency of leaning between any other task hand locations.

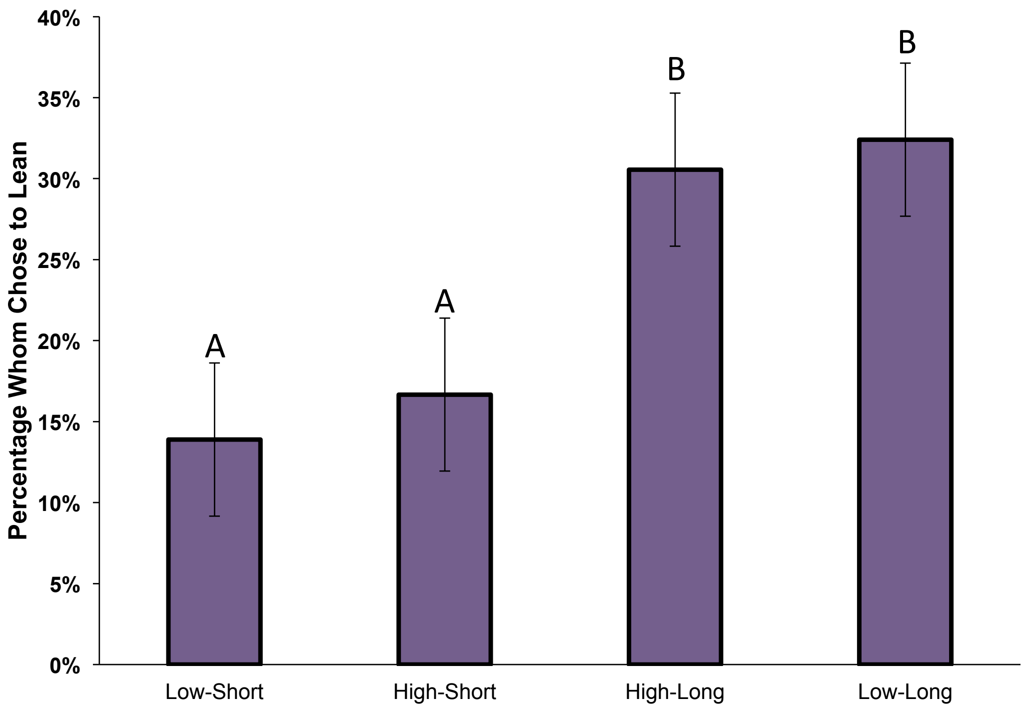

Figure 13: The main effect of Location on the percentage of participants that chose to lean (n=18), displayed in ranked order from lowest to highest. Significantly different means are indicated with the different letters. Standard error bars are displayed.

There was also a Direction main effect for the percentage of participants that chose to lean. Significantly more people chose to lean during the Pull force exertion direction than the Down force exertion direction (p<0.05) (Figure 14).

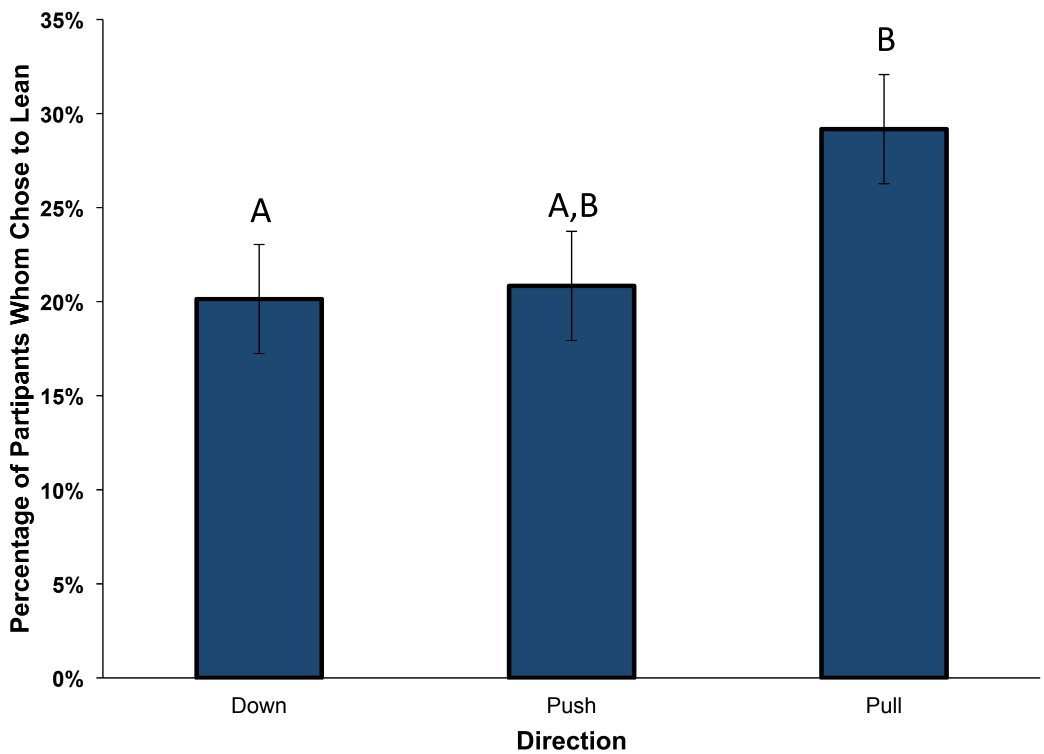

Figure 14: The main effect of Direction on the percentage of participants that chose to lean displayed in ranked order from lowest to highest (n=18). Significantly different means are indicated with the different letters. Standard error bars are displayed.

The logistic regression analysis produced a model that explained 70.3% percent of the variance in the choice to lean and was able was able to correctly predict 92.2% of the individual leaning choices (n = 477, Table 3). Elbow-flexion strength, trunk extension strength, push and pull force exertion direction and task hand reach (as a percent of arm length) were all significant predictors in the analysis (p<0.05) (Table 3).

Table 3: Logistic Regression summary with all variables inputted into the equation

Logistic Summary Table for Choice-0NL-1L	
Count	477
# Missing	0
# Response Levels	2
# Fit Parameters	17
Log Likelihood	-79.885
Intercept Log Likelihood	-269.055
R Squared	0.703

	Coefficient	Standard Error	Coef/SE	P-Value
Constant	255.051	30650.552	0.008	0.993
Hand Force	0.019	0.014	1.318	0.187
Arm Length	3.079	620.417	0.005	0.996
Height	-5.439	436.266	-0.012	0.990
Mass	6.180	131.496	0.047	0.963
Shoulder-Flexion-Strength	-2.078	70.625	-0.029	0.977
Shoulder-Extension-Strength	3.883	9.591	0.405	0.686
Shoulder-Abduction-Strength	-2.620	122.653	-0.021	0.983
Shoulder-Adduction-Strength	-3.479	113.890	-0.031	0.976
Elbow-Extension-Strength	-4.280	64.139	-0.067	0.947
Elbow-Flexion-Strength	5.716	.	.	.
Trunk-Extension-Strength	1.045	.	.	.
Trunk-Flexion-Strength	-0.458	0.295	-1.553	0.120
Push/Pull Force Exertion Direction	-0.955	0.265	-3.609	0.000
Up/Down Force Exertion Direction	0.483	0.418	1.156	0.248
Task Hand Height as a percent of Stature	1.685	1.727	0.976	0.329
Task Hand Reach as a percent of Arm Length	10.472	1.591	6.583	<.0001

4.2 Leaning and the Task Arm

Leaning significantly influenced both task arm resultant shoulder moment and elbow flexion angle. There was a significant decrease in task arm shoulder moment for Lean (9.6 ± 5.2 Nm) compared to No Lean (10.4 ± 5.5 Nm) ($p<0.0001$). Task arm elbow flexion angle was significantly higher for Lean (60.4 ± 14.8 deg) compared to No Lean (52.2 ± 13.1 deg) ($p<0.0001$).

There was a Lean x Location interaction for task arm resultant shoulder angle ($p<0.01$). When compared to No Lean, rotations were significantly lower for Leaning only at the Low-Long task hand location. There was also a Lean x Direction interaction for trunk flexion angle. Trunk flexion was significantly higher during only Pull exertions when Leaning, compared to No Lean ($p<0.05$).

There was a Lean x Location x Force interaction for resultant trunk moment. Leaning decreased trunk moment for all Long reach task hand locations ($p<0.05$) (Figure 15). At the low force level (27.5 N) trunk moment was significantly lower with Leaning, compared to No Lean, at the High-Long and Low-Long task hand locations. In addition, trunk moment was significantly higher with Leaning, at the Low-Short task hand location. At the high force level (55 N) trunk moment was significantly lower when Leaning, compared to No Lean, at the High-Long, High-Short and Low-Long task hand locations.

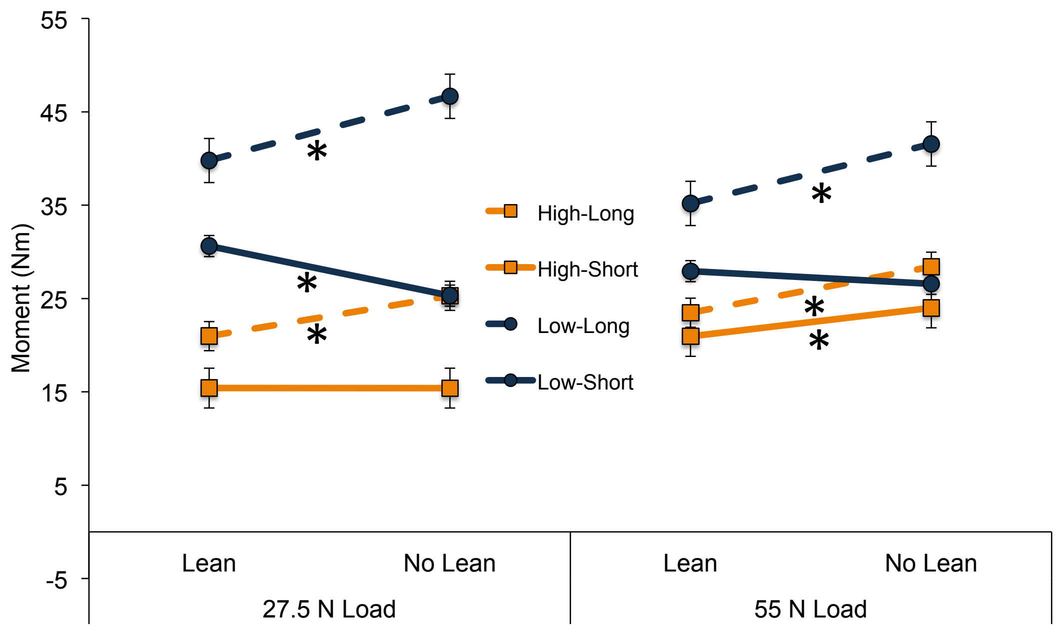

Figure 15: The 3-way interaction between Lean, Location and Force for the mean resultant trunk moment (n=20). The asterisk demonstrates a significant difference in resultant trunk moment between lean and no-lean conditions. Standard error bars are displayed.

4.3 Leaning Hand Forces and Leaning Hand Heights

In general, the leaning hand resultant force was greatest during Pull exertions. Leaning hand forces, as a percentage of body, mass are displayed in Figure 16 for each Direction. When pooled across all trials, participants leaned with an average 5.5 ± 1.7% of body weight (%BW). The pooled averages for Down, Pull and Push were 4.1, 8.9 and 3.5%BW, respectively. The average leaning hand resultant force, and height for each separate leaning condition, are displayed in Appendix D. Across all of the leaning trials, participants placed their hand on the horizontal shelf approximately 30% of the time and used the vertical surface the other 70% of the time.

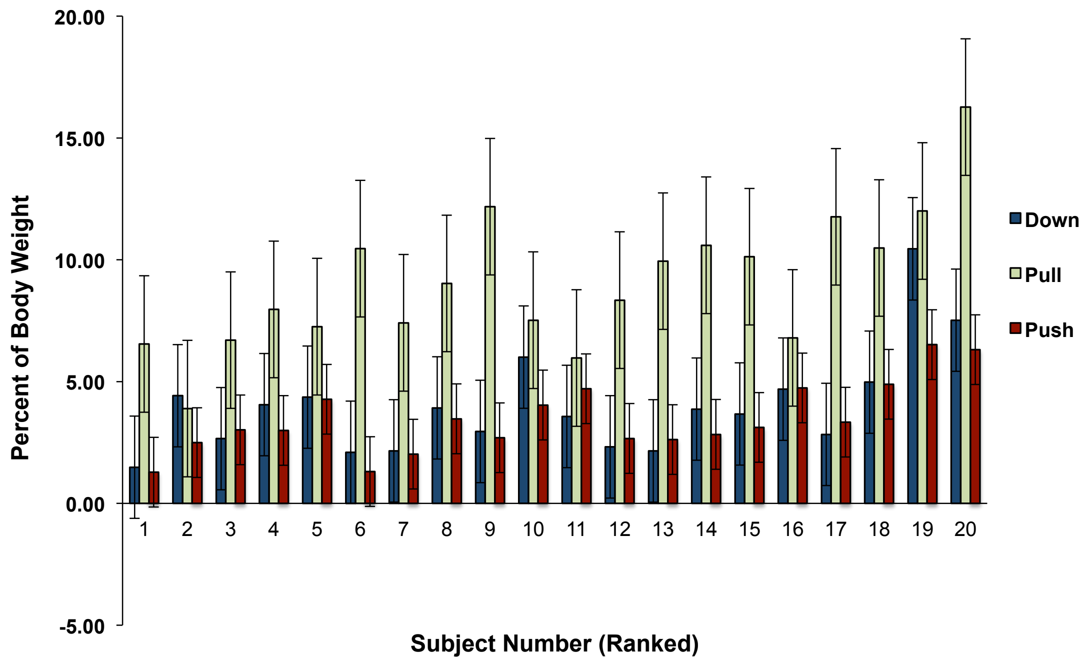

Figure 16: Average resultant leaning hand force, as a percentage of body weight, for each subject for each of the three force exertion directions. Subjects are displayed in ranked order from lowest to highest average leaning hand resultant force (pooled across Directions). Standard error bars are displayed.

There was a Location x Direction interaction for leaning hand resultant force ($p<0.0001$). At each Location, participants applied a larger leaning force for Pull when compared to both Down and Push exertions (Figure 17). There were no significant differences between Down and Push exertions at any of the 4 hand locations.

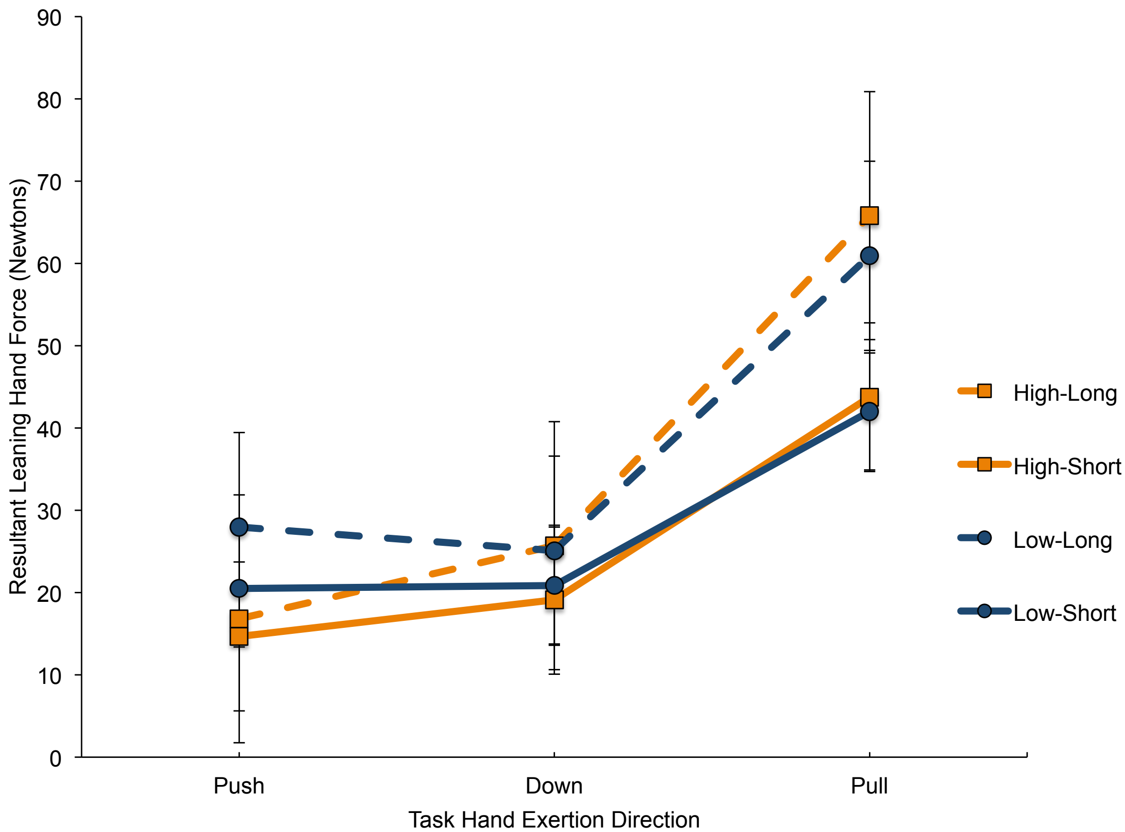

Figure 17: The interaction between Location and Direction for the average leaning hand resultant force (n=20) Force directions are displayed in ranked order from lowest to highest average leaning hand resultant force. At all of the task hand locations, the leaning hand force for Pull was significantly higher than Down and Push force exertions. Standard error bars are displayed.

There was also a Direction x Force interaction for leaning hand resultant force ($p<0.0001$). At both the 27.5 N and 55 N force levels, participants applied a much larger leaning hand force for Pull compared to Down and Push exertions (Figure 18). There was no significant difference between Down and Push exertions.

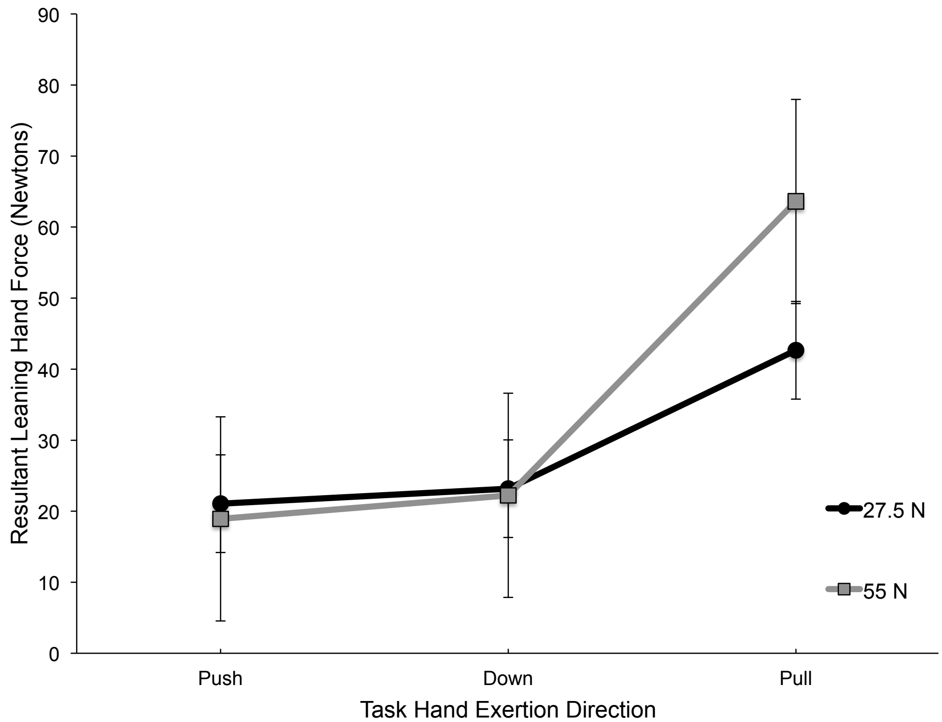

Figure 18: The interaction between Direction and Force for average leaning hand resultant force (n=20). Force directions are displayed in ranked order from lowest to highest average leaning hand resultant force. For both the 27.5 and 55 N forces, Pull exertions had a significantly higher resultant leaning hand force than Push and Down. Standard error bars are displayed.

There was a Location main effect on leaning hand height (Figure 19). Leaning hand height was significantly higher at the High-Long task hand location when compared to the Low-Short task hand location ($p<0.05$). There were no significant differences in leaning hand height between any of the other task hand locations. In general, leaning hand height followed the height of the task hand. With the highest leaning hand height at the High-Long task hand location (116.3 ± 16.7 cm) and the lowest leaning hand height at the Low-Short task hand location (106.6 ± 14.4 cm) (Figure 19).

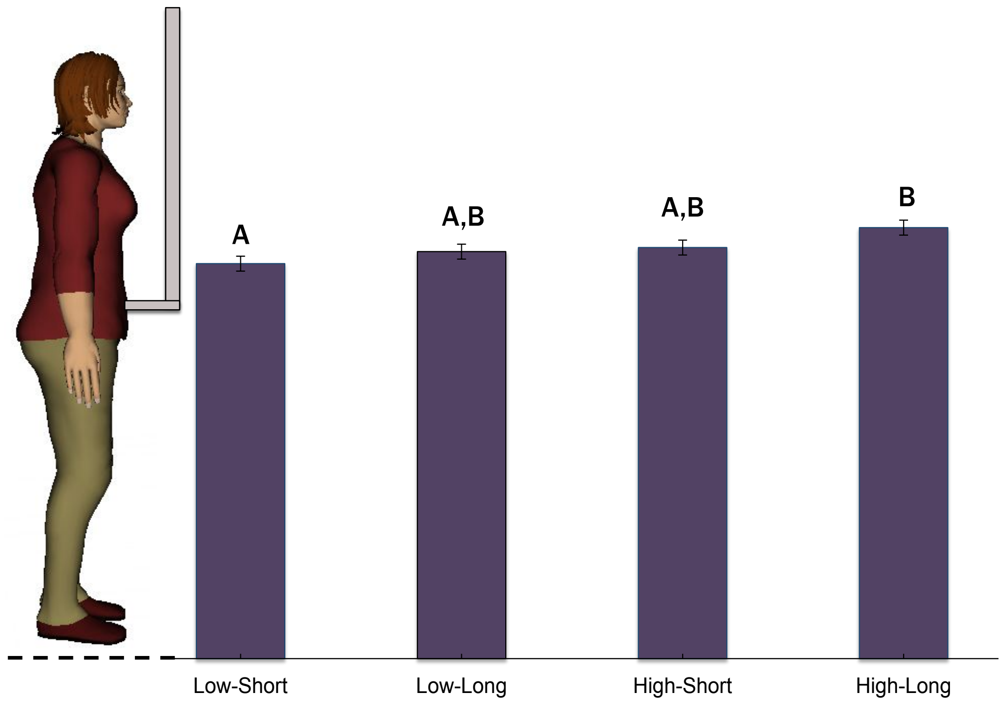

Figure 19: A pictorial representation of where the average leaning hand height would be on a 75th percentile female, for each task hand location. The approximate location of the leaning surface is also displayed. The bottom of the horizontal leaning surface was placed 10 cm above wrist height. The graph displays a location main effect (n=20). Significantly different means are indicated with the different letters. Standard error bars are displayed.

4.4 Demands placed on the Leaning Arm

There was a Location main effect on leaning arm elbow flexion angle, and leaning arm resultant shoulder angle (Figure 20). Leaning arm elbow flexion angle was significantly greater at both Long reaches compared to both Short reaches. Leaning arm resultant shoulder angle was significantly greater at the Low-Short versus the High-Short task hand location ($p<0.0001$).

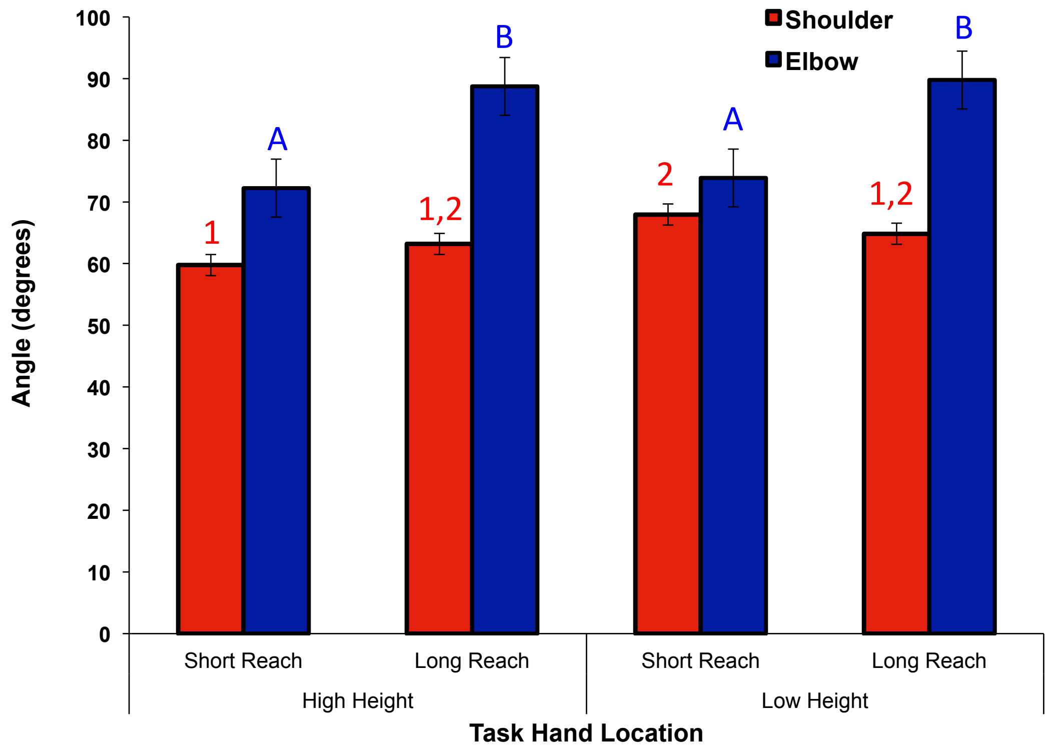

Figure 20: The mean elbow flexion angle and mean resultant shoulder angle showing a location main effect (n=20). Means indicated with the different letters or numbers are significantly different. Standard Error bars are shown.

There was a Direction main effect on both leaning arm elbow flexion angle and resultant shoulder angle. Elbow flexion was significantly greater during the Pull exertions when compared to the Push exertions ($p<0.05$). Leaning arm resultant shoulder angle was significantly higher during Pull exertions when compared to both Down and Push exertions ($p<0.05$). Down exertions also displayed a significantly higher shoulder angle when compared to Push exertions.

There was a main effect of Force on leaning arm elbow flexion angle as it was significantly higher at the 55 N versus 27.5 N ($p<0.01$). There was a Location x Direction interaction with both leaning arm elbow flexion moment (Figure 21) and resultant shoulder moment (Figure 22). At all task hand locations, elbow flexion moment and resultant shoulder moment were significantly higher during Pull exertions when compared to Push and Down exertions (both $p<0.05$).

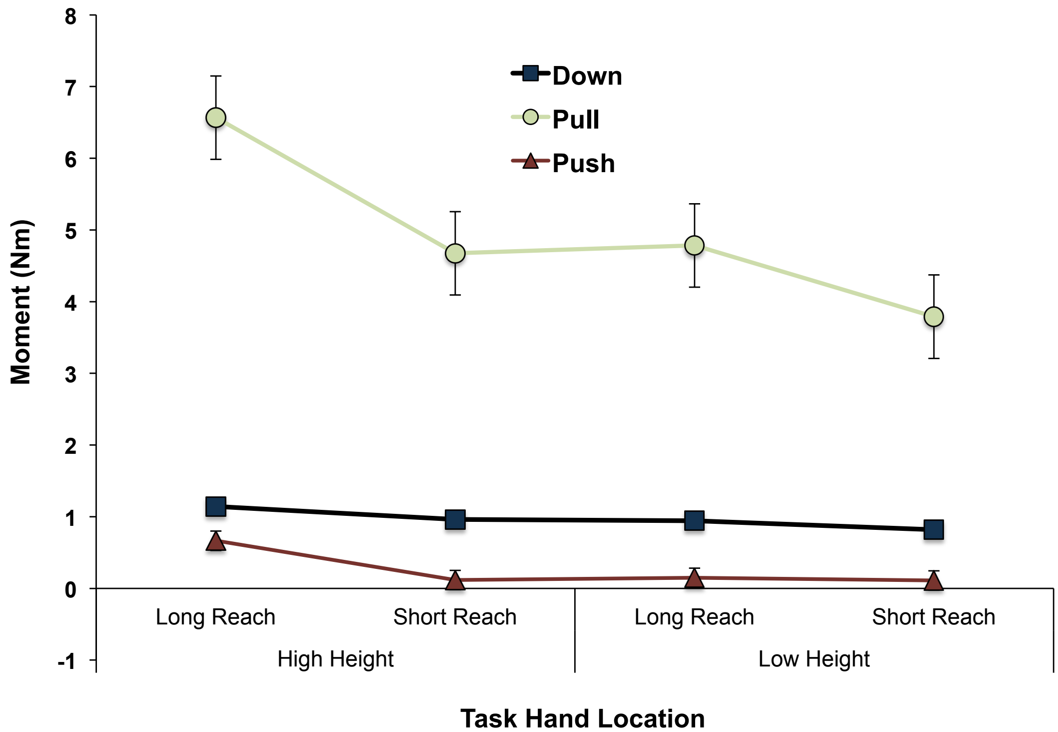

Figure 21: The Direction x Location interaction for mean leaning arm elbow flexor moment (n=20). Pulling always resulted in significantly higher moments than Down and Push directions. Standard error bars are displayed.

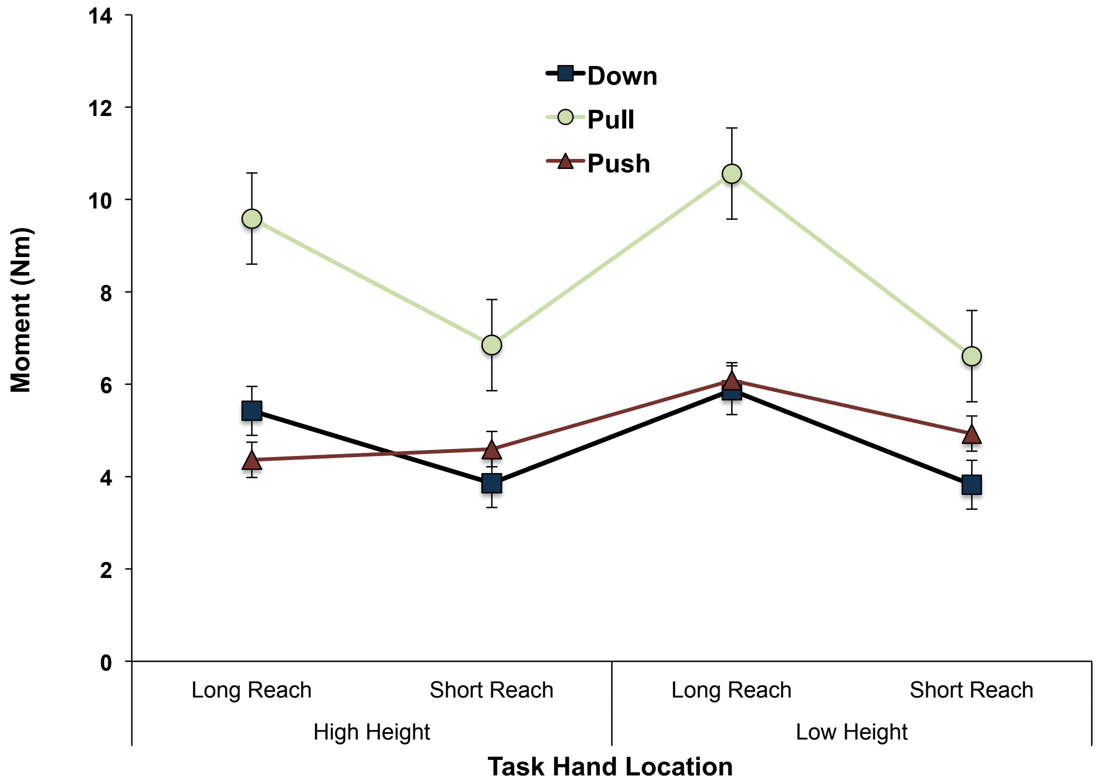

Figure 22: The Direction x Location interaction for mean leaning arm resultant shoulder moment (n=20). Pulling exertions always resulted in significantly higher moments than the Down and Push directions. Standard error bars are displayed.

There was a Direction x Force interaction for both leaning arm elbow flexion and resultant shoulder moments. At both the 27.5 N and 55 N force levels, average elbow flexion and shoulder moments were significantly higher during Pulling compared to the Down or Push directions ($p<0.0001$)

Chapter 5 – Discussion

The most important findings of this study were: 1) a logistic regression was developed, with the input of individual subject anthropometry and task characteristics and the resulting model was able to provide a very accurate prediction of when an individual would lean, 2) the long reach locations resulted in the most frequent choice to lean, and this decreased trunk and task arm shoulder loading, and 3) leaning hand forces were highest during pulling tasks. These findings are very important to document, as current ergonomic tools neglect to consider that different task characteristics may change how, and when, a worker chooses to lean. Even when only the direction of the task hand force was changed, leaning hand forces differed significantly. In this study, leaning hand height was slightly higher for the shoulder height, when compared to the umbilical height, task hand locations. The height of the leaning hand did not vary considerably and ranged between 106.6 cm to 116.3 cm. The amount of leaning hand force changed as task hand location, force direction and force level changed. Leaning hand forces increased with increasing task hand load. Task hand forces in the push direction had higher leaning hand forces compared to push and down exertion directions regardless of task hand location or task hand load.

5.1 What Happens When People Lean?

This was the first study to document the freely chosen height of the leaning hand. The shoulder height task hand locations resulted in slightly higher leaning hand heights than when the task hand was at umbilical height (Figure 19). This study used specific body landmarks (shoulder and umbilical) to determine the height of the task hand. When looking at the average landmark heights used in this study, and comparing them to the height of a 50th percentile female, shoulder and umbilical heights ended up being, on average, 85% and 62% of stature, respectively. Relative to a 50th percentile female stature, the height of the leaning hand was, on average, 71%, 67%, 67% and 65% for the High-Long, High-Short, Low-Long and Low-Short task hand locations, respectively (Figure 19).

Across all of the leaning trials, participants placed their hand on the horizontal shelf approximately 30% of the time and used the vertical surface the other 70% of the time. The horizontal shelf was placed 10cm above the average wrist height of approximately 48.5 percent of stature. Even accounting for the additional 10 cm of height, the horizontal surface was still placed lower than any of the average leaning hand heights (the lowest average leaning hand height was 65% of stature). In fact, to add a comparison to the leaning hand heights mentioned above, for a 50th percentile female the horizontal leaning surface would have been placed at 55% of stature. It is possible that the optimal height of the horizontal surface was underestimated and that in reality the surface should have been placed higher.

Leaning hand forces also changed as the task hand load changed and ranged from 3.6 to 8.9% of body weight (Figure 16). These forces were slightly lower, when compared to previous results from leaning studies that have documented leaning hand forces as a percentage of body mass (Godin et al. 2008, Fraser et al. 2003). Fraser et al. (2003) determined that leaning hand forces ranged from 10 to 15% of body weight when completing a one handed bolt fastening task. Godin et al. (2008) studied leaning during four very specific occupational tasks and reported that leaning hand force levels ranged from 5.5 to 12.1% of body weight. Those two previous studies did not report task hand forces, however, the lower leaning hand force levels in the current study may be attributed to the fact that this current study used lower task hand forces, than the two previous studies. Those studies used specific tasks, including, engine hose installation, intermediate shaft secure into the steering gage, various electrical connections and one handed bolt fastening tasks. These types of tasks might have warranted a larger task hand force. In the current study, larger leaning hand forces were observed for the 55 N task hand load when compared to the 27.5 N task hand load (Figure-Results).

Jones (2011) investigated the effects of leaning and bracing surfaces on maximum task hand force capability, and found that increased task hand force levels were associated with increased leaning forces. Jones (2011) actually reported that task hand force was a significant predictor of leaning hand force across all task hand force directions. It is also possible that leaning hand forces change as task complexity changes or as task duration changes. The studies performed by Godin et al. (2008) and Fraser et al. (2003) would have both had longer and more complex task durations, when compared to this study. These task differences cannot be ruled out as possibilities for my finding of lower leaning hand force levels.

5.2 Leaning Hand Changes with Task Demands

To date no study has kept the task hand force constant and investigated how leaning hand forces change. This study found that leaning hand forces, and the resulting leaning arm shoulder and elbow moments, were higher with pulling versus down and push exertions (Figure 21, Figure 22). This finding was consistent across all force levels and task hand locations and demonstrates that, while leaning has benefits for the task arm and low back, there are also potential loading tradeoffs for the leaning arm that become more evident in tasks that warrant higher leaning hand forces.

The down forces resulted in the lowest leaning hand force and the lowest choice to lean. Participants chose to lean most frequently during pulling tasks (Figure 14). This result was somewhat surprising, as the down force vector would have had the largest moment arm about the task shoulder and elbow, resulting in a larger moment at the task shoulder and elbow. Based on the large moment produced at the task arm shoulder and elbow, during down force exertions, it was assumed that leaning might benefit down force exertions the most, as it would help distribute the load across the task arm and leaning arm.

Fischer et al. (2012), demonstrated that down force exertions are generally limited by strength and that pushing and pulling exertions are limited by whole body balance demands. The relatively low force levels used in this study would have not usually been limited by strength. Down force exertions are typically not limited by balance due to the fact that the resulting upwards force on the hand would create a moment acting backwards, which would not likely put them out of balance given that they are leaning forward. Thus, leaning during down force exertions probably would have served no benefit to the participant and this is probably why the percentage who chose to lean, and the leaning hand forces, were lower for down exertions.

Leaning hand forces were higher for the pulling exertions. One explanation could be that leaning was necessary to maintain postural stability, as the counter reaction force would tend to move the center of pressure forward, by creating a forward moment and potentially putting the participant off balance. A leaning force would create a backwards moment to counteract the shift in center of pressure. The premise that leaning may be beneficial to balance during pulling tasks is supported by the finding that trunk flexion was lower during pulling tasks with leaning, compared to no leaning. In addition to having a force on the leaning hand, to prevent shifting of the center of pressure, it helps the participant stay upright and maintain balance by keeping center of pressure under the feet.

In contrast, for pushing exertions, there was no handle on the leaning surface to create a counterbalance with (ie: a handle would have allowed participants to pull backwards with the leaning hand while pushing forward with the task hand). The only case when a leaning surface would benefit in a push task would be when it is necessary to put your body weight into the exertion and maintain balance. The force exertion levels in this study were not maximum forces, and would not have gotten to the point where center of pressure was so off balance such that participants would lean to help maintain balance. Based on the results discussed it appears that at the lower fixed force levels the choice to lean seems to be related to helping to maintain whole body balance.

Jones (2011), found that leaning increased force-exertion capability, depending on the task hand force direction and task handle location. Jones (2011) demonstrated, that when permitted to do so participants lean in such a way that increases force exertion capability. Jones (2011), suggests that this increase in task hand capability is due to the fact that when leaning, oppositional forces are generated at the leaning hand and leaning surface that enables an increase in resultant task hand force magnitude. When a leaning surface is not available the task hand force exertion is derived from body and ground reaction force only. Unlike the Jones (2011) study, this investigation used fixed force levels. When looking at this study, it appears as though the oppositional forces generated when leaning are still seen as beneficial, but are used more for whole body balance at the lower fixed force levels.

5.3 The Relationship Between Leaning Arm, Task Arm and Trunk Moments

As noted, leaning decreased task hand resultant shoulder moment. This was a very significant and interesting finding as this was the first study to report the load on the task hand shoulder with and without the availability of a leaning surface. While the decrease in shoulder demand with leaning was small, it is important to consider that the force levels used in this study were low when comparing at each exertion on an individual basis. The force levels used in this study were purposely chosen to represent the type of force levels seen in automotive assembly tasks, however these types of tasks are often performed very frequently. It is likely that, as the demands placed on the task hand increase, leaning may serve as a greater benefit to the task arm shoulder. In this study, the task hand forces were kept at fixed loads. Since the force loads stayed constant (between leaning and no leaning conditions) the only thing that would change is the moment arm with respect to shoulder moment. Therefore, shoulder angle would be the contributing factor to the observed decrease in shoulder moment when leaning.

It has been well documented that leaning can decrease spinal loading, (Howard et al. 2012, Ferguson et al 2002, Kingma & van Dieen 2004). The current study also confirmed this, but only for the two long reach task hand locations with both Loads (Figure 15). Leaning had little effect on resultant trunk moment at the two close locations and, in one condition (Low-Short, 27.5 load) leaning actually increased trunk moment. It is possible that that combination of Location and Load did not require leaning, and that participants got into a more unnatural posture when forced to lean when, in reality, they would have probably chosen not to lean. In fact, in this study, out of all of the combinations of task hand loads and locations, the Low-Short 27.5 load condition had the lowest frequency of choice to lean (11.1%). This result is important to note because it demonstrates that leaning must be considered on a task condition basis, and may not always be beneficial. This also demonstrates the benefits of my study design, and suggests that participants should be given a choice to lean to get a true indication of when leaning is beneficial. All of the previous investigations that have confirmed decreased spinal loading when leaning involved longer reaches and/or constrained tasks (Lardi & Frazer, 2003, Kingma & van Dieen 2004).

In addition to lowering some joint demands, there was more task arm elbow flexion when leaning versus no leaning. It is likely that participants were able to (and also chose to) get closer to the task handle when able to do so via leaning. Participants also chose to lean the most at the Low-Long task hand locations followed by the High-Long task hand locations. Thus, leaning appears to be particularly common, and important, when long reaches are required, as they can reduce task hand shoulder and trunk demands by allowing the worker to get closer to the task. When a leaning surface was available, the participant was able to shift their center of pressure forward, because it is counterbalanced by the lean. This allowed the participant to maintain balance and get their body closer to the task handle without flexing the trunk. Without leaning, to keep the center of pressure between the feet and maintain balance, you would need to squat and flex the trunk forward with a more extended arm position. Thus, the resultant shoulder rotation would be higher (resulting in a larger shoulder moment when not leaning).and the elbow angle would be more flexed, placing the participant closer to the task and requiring a lower elbow moment. Long reaches are the types of tasks that can offset balance and create the highest demands on the shoulder. This is most likely why the study observed more benefits to the task arm when leaning during the longer reaches.

It is important to put the magnitude of the moment demand changes into context. The mean difference between shoulder moment when leaning and no-leaning was 0.8 Nm. The mean difference in trunk moment between leaning and no-leaning for the Low-Long and High-Long locations and 27.5 load were 6.9 and 4.3 Nm, respectively. The mean differences in trunk moment, between leaning and no-leaning for Low-Long and High-Long locations with a 27.5 load, were 6.4 and 4.9 Nm, respectively, None of these difference were large but, keeping in mind that this represents a single 1–3 s exertion, it could become significant when accumulated over time, possibly making the difference between injury or no injury. Most occupational tasks require repetitive efforts. For example, in automotive assembly plants, the cycle times are usually close to 60 seconds such that, even if the frequency of a particular effort is only one per cycle, the worker performs about 400 of these efforts each workday. Potvin (2012) found a strong negative relationship between duty cycle (the percentage of time an individual is engaged in a particular effort) and maximum acceptable efforts. The relationship demonstrates a very rapid decline for maximum acceptable efforts at low duty cycles. Leaning during these high frequency tasks may decrease cumulative loading on the task arm and trunk and, most importantly, decrease acute and/or chronic injury risk.

To date, Jones (2011) is the only other study that has investigated how a kinematic constraint, such as a leaning surface, affects task completion. The current study was specifically designed to fill in some gaps, and address some limitations, from the leaning portion of the Jones (2011) study. Jones (2011) investigated forces at 50% and 100% of maximum, whereas this study used fixed force levels to make this study more applicable to industry. Despite the differences, several comparisons and conclusions can be made between this study and Jones (2011). Jones (2011), reported that the results from their investigation strongly supported their hypothesis that leaning hand forces are primarily used to generate forces opposing task hand force, rather than to support the body. They found that the existence of a leaning surface enabled participants to modify postural behaviours and effectively assist the person in preforming maximal exertions. In comparison, the current study did find that the availability of a leaning surface modified postural behaviours, however the postural modifications that did accompany leaning appeared to assist the person in maintaining whole body balance and lower moment demands on the trunk and task arm shoulder.

The contrast the current findings, with those of Jones et al (2012), suggest that the reason people lean may change as task hand force demands change. Jones (2011), found that leaning had the largest impact on task hand force capability when exerting upward (up to a 60% increase in task hand force when leaning). Pulling tasks had the second largest increase in task hand force generation capability (44%), followed by pushing tasks (14%). While my study did not investigate upward task hand direction, we can compare the pushing and pulling results. Based on both my study and Jones (2011), it appears as though leaning can be beneficial for pulling tasks regardless of the force demand, while pushing tasks appeared to benefit very little form a leaning surface. This supports the hypothesis that the use of a handle for support, when performing pushing tasks, may serve more benefit. A handle would allow the opportunity for participants to generate oppositional forces that could aide in balance and force-exertions capability. Jones (2011) did not investigate downward force exertion directions. Mine was the first study to investigate downward force exertions with the availability of a leaning surface. It is interesting that Jones (2011) noted that leaning served the largest benefit during upward exertions, but my study showed very little benefit to downward force exertions. Upward exertions, similar to downward exertions, would not be limited by balance. This result might expand upon the hypothesis that leaning may serve the greatest benefit, to tasks that do not limit balance, by increasing force exertion capability. In short, while this study is not directly comparable to the results found by Jones (2011), it has added some valuable insight to how and when people chose to lean and provided data on conditions not tested by Jones (2011).

5.4 Applications to Industry

This study was performed to, in part, assist ergonomic practitioners in estimating when a worker would lean, with what force they would lean with, and where the preferred location of the leaning hand would be. This study used a logistic regression to get a very good prediction of when an individual would lean. This is a significant finding, and very pertinent to industry. The logistic regression model had a 92% success rate for predicting when a participant would chose to lean for each condition within this study.

Elbow-flexion strength, trunk extension strength, push and pull force exertion direction and task hand reach (as a percent of arm length) were all significant predictors in the analysis. The model displays that the likelihood of an individual choosing to lean increases as the length of the reach for the task hand increases and for pulling versus pushing tasks. This result would be expected, as the data presented above demonstrated that leaning was most beneficial during long reaches and pulling tasks.

In addition, some individual elbow flexion strength and trunk extension strength values also explained a significant portion of the variance in leaning choice. Typically, when given the choice to lean or not, participants were very consistent with their choices. In other words, some subject used the leaning option almost every time, and other subjects almost never did. This is probably why strength values became important predictors within the logistic regression model. The strength measures were one of the only individual factors that were included into the logistic regression model. Trunk extension strength would be good a good predictor for leaning because, as seen from this study, leaning helps the participant stand more upright. It is likely that those with higher low back strength also had higher elbow flexion strength and therefore the strength values defined the subset of the population that would chose to lean.

The second objective of this study was to collect representative leaning hand forces and locations to be used to guide ergonomists in proactive ergonomic assessments. The average leaning hand height stayed relatively consistent throughout all of the task hand conditions and ranged from 106 to 116cm. The horizontal leaning surface was placed slightly lower than the range of leaning hand heights noted above. As a result this surface was only used during 30% of all the leaning conditions. It is possible that participants have a very narrow range where they feel it is most comfortable to place the leaning hand. Using a leaning surface outside of this range, in the case of this study, appears to be not preferred. This finding can be very useful to ergonomists as it demonstrates that people tend to lean at a consistent leaning hand height for a wide array of tasks. This study also documents representative leaning hand forces, and how they change as task demands change. Pulling tasks had the largest leaning hand force and the most frequent choice to lean.

The oppositional forces, generated by the leaning hand against the leaning surface, were used to support the body weight to counterbalance and maintain balance during pushing tasks. Now that there is some indication of the types of leaning hand forces people use when performing a task, ergonomists can make a better prediction of what the leaning hand forces would be when performing proactive ergonomic assessments. The study also demonstrates that workers might use leaning as an aide to maintain balance. Therefore it might be beneficial to consider the use of a handle for the leaning hand during pushing tasks.

This study evaluated the postural strategies used during constrained reaching when a leaning surface is available. Typically, participants flexed less with their trunk when leaning, and stood more upright. This likely allowed them to shift their center of pressure forward over the foot, to get the whole body closer to the task. This resulted in an increase in elbow flexion, since the task arm did not have to reach out as far, and decreased shoulder rotations, lowering shoulder moments. These findings provide some great insight into the posture selection process when a leaning surface is available. Typically, it was seen that postures selected, when a leaning surface was available, were geared to maintain whole body balance.

One of the most important findings from this study, with respect to industry, is that it has contributed some insight into the priorities set for leaning when a leaning surface is available. It appears as though leaning forces, at the lower, fixed force levels, are used to aide with whole body balance. Insight from Jones (2011), indicates that, as task hand force levels reached maximum, leaning was used as a strategy to increase task hand force capacity. Knowledge of the priorities set for leaning might inform a cognitive posture prediction model in the future. This study collected full body postures when leaning. The joint angles, and force magnitudes associated with these postures could be used in the future to drive ergonomic posture prediction software.

5.5 Limitations and Future Directions

Future studies on leaning should continue to investigate task with longer reach requirements, as these types of task hand locations appear benefit most when a leaning surface is available.

There was a lower proportion of participants whom chose to lean than expected (out of all tasks completed only 25% freely chose to lean). This study only required two loads on the task hand (27.5 N and 55 N) held for a short period of time. Automotive assembly workers often perform the same task multiple times per minute for 8 hours a day. Participants in this study might not have become familiar with the “routine” of the task where they would have thought leaning would serve a benefit. In addition, the low frequency of participants choosing to lean could also be due the fact that one training session was not adequate for the participant to feel comfortable with the task. Auto assembly workers are very familiar with the tasks they perform, as they perform them over and over. It is possible that participants in this study were too focused on the task exertion directions and did not consider leaning, as it would have been an additional distraction to focus on. Automotive assembly workers would be very familiar with their task and, thus, external factors such as leaning would not be as disrupting.

A future study should investigate different task hand loads over a longer period of time. This would hopefully promote more participants choosing to lean. In addition, understanding leaning during a variety of task loads will allow the investigators to understand if leaning can continue to serve a benefit to the task arm shoulder and decrease task arm resultant shoulder moments. Potvin (2012), has developed an equation to predict the maximum acceptable efforts using duty cycle as the only input variable. It performed very well for a wide variety of repetitive upper extremity task demands. The equation outputs can be multiplied by maximum strength data (from the literature or directly measured) to predict the absolute magnitude of maximum acceptable force levels, for repetitive tasks

(Potvin, 2012). Using this equation in a future leaning study would be beneficial to predict what the loads should be, based on the length of the study and the number of exertions to be performed. Varying the length of time to complete the study, and the load of the task hand would continue to give investigators insight on how leaning benefits the task arm and promote more participants to chose to lean. Finally, it is also suggested that a full separate day be dedicated to training the participant in the task to be completed. The training session should involve completing all of the tasks under investigation, multiple times, without the use of the leaning surface and with the use of the leaning surface. This will allow the participant to get a good idea of when leaning is beneficial to them and when it isn't.

This study investigated push and pull exertion directions because a recent field survey found that these task hand force directions most frequently involved leaning (Cappelletto et al. 2012). This study included down force exertions because no study had done this previously. However, this study did not investigate right, left or up force exertion directions. It would be beneficial to study these additional exertion directions, as this study has already demonstrated that a very complex interaction occurs between leaning hand location, task hand force exertion direction and task hand force level.

In addition, the logistic regression still needs to be validated. In the future, two of the participants from this study will be removed from the equation. These two participants will then be used to test the logistic regression to see if the model will be able to accurately predict which conditions that participants leaned and which conditions they did not. The main goal of this initial logistic regression analysis was to get some indication of what factors are important to consider when someone choses to lean. The logistic regression has accomplished this and future work will go into validating the model.

Chapter 6 - Conclusions

In conclusion, this study added to the literature leaning hand forces and heights for a variety of generalizable tasks. This is of particular use to industry as ergonomists now have representative forces and heights, to help guide leaning estimates during proactive risk assessments. In addition to these forces and hand heights, the logistic regression provided a model that was able to make good predictions of when an individual would lean based on their own characteristics and the specific task conditions. The inputs to this model give insight into what factors are important in the decision making process when a worker chooses to lean or not. Leaning appears to be particularly common, and important, with long reaching and pulling tasks that can reduce task hand shoulder and trunk loads and improve balance, while allowing the worker to get closer to the task. In addition a logistic regression demonstrated that individual differences also play an important role in predicting leaning, specifically, trunk extension strength and elbow flexion strength are important factors.

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Appendix A: Participant Anthropometrics and Strength

		Anthropometrics						Strength							
Subject Number	Age	Height (cm)	Weight (kg)	Arm Length (cm)	Shoulder Width (cm)	Shoulder Height (cm)	Umbilicus Height (cm)	Shoulder Flexion Strength (Nm)	Shoulder Extension Strength (Nm)	Shoulder Abduction Strength (Nm)	Shoulder Adduction Strength (Nm)	Elbow Extension Strength (Nm)	Elbow Flexion Strength (Nm)	Trunk Extension Strength (Nm)	Trunk Flexion Strength (Nm)
1	24	168	61.3	70	29	139	102.2	51.8	68.2	31.9	44.1	48	38.8	140	70.8
2	21	152	53	66.5		125	91.5	46.2	47.1	36.3	42.4	38.5	35.3	189.3	68.7
3	22	150	54.5	63.5	34.3	122	89	46.8	51.8	47.5	48.3	35.8	42.6	127.3	51.5
4	25	162	56.8	69.5	30	137.5	100.5	38.6	58.2	47.2	35.1	40.4	30.8	119.3	83.5
5	28	161	68	72	29.5	139.2	99.7	45.3	52.7	60.7	52.3	35.7	34.7	186.2	90.2
6	24	168	63.2	73	31	139.5	101	40.5	57.5	37.3	49.5	44.9	37.6	104.1	64.3
7	26	177	65.9	75.5	33	147.5	102.3	42.8	54.8	31.1	42.7	33.5	33.1	151.9	93.2
8	20	159	70	65	31	136	94	40.4	43.9	37.2	54.9	34.5	32.7	139.7	53.4
9	25	165	53.2	71.5	28	135	100	45.3	59.1	38.2	57.2	44.6	40.8	207.9	86.5
10	25	175	65.9	83	29	146	111	70.6	58.7	44.1	61	36.1	49.2	168.7	77.8
11	21	158	56.8	72.5	26	135	100	37.3	48	35.3	40.8	32	29.2	116.5	62.4
12	29	160	60	70.5	28	134	99	53.8	68.5	51.1	60.6	59.8	57.1	172.3	101.1
13	20	179	62.7	76	39	145.5	106	53	55.6	29	43.7	50.9	43.1	196.2	71.2
14	23	168	70.5	76	30	144	105.5	53.2	63.9	45.2	67.3	43.4	49.6	84.2	69.8
15	23	167	52	73	23	142	101	33.1	38.5	45.7	42.6	37.8	21.6	182.1	59.4
16	22	180	77.3	80	28	152	114	52.1	48.7	37.8	50.9	37.8	21.6	242.3	119.5
17	24	170	64.5	77.5	29	144	104	42.6	54.2	37.7	51.8	41.6	34.4	93.6	71.9
18	24	158	53.6	70	27	136	97.5	47.3	47.3	30.4	38	29.7	30.4	95.7	67.9
19	26	163	52.3	75	24	142.5	103	50.4	64	49.5	55.2	39.1	36.3	112.1	67.3
20	19	166	50	71	27	136	99.5	30.6	32	36.1	32.3	28.7	26.6	70	104.3
Average	24	165.3	60.6	72.6	29.3	138.9	101.0	46.1	53.6	40.5	48.5	39.6	36.3	145.0	76.7
Standard Deviation	2.6	8.3	7.6	4.8	3.6	7.2	5.8	8.8	9.4	8.1	9.2	7.5	9.1	46.7	17.8

Appendix B: Letter of Information and Consent

June 12, 2013

Letter of Information and Consent

An Investigation of postures during one-handed submaximal exertions with extended reaches

Investigators: Dr. James Potvin & Kayla Fewster

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Purpose of the Study

The goal of this study will be to understand the postures and strategies that are adopted by humans during a one-handed task. This study will evaluate the whole-body postures adopted for four specific hand locations. The direct applications and implications of this research includes the improvement of ergonomic tools that are in use today. Currently, very important ergonomic decisions regarding job tasks are being made with no validation on what the associated postures are. This research will go a long way towards improving the validity of ergonomic tools, thus lowering the incidence of work-related injuries.

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

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

You will stand in front of the experiment apparatus. With your dominant hand, you will grip a padded handle that is mounted to a force plate. The force plate will be used to measure the force that you are exerting on the handle.

During the protocol, you will be asked to apply force on the handle attached to the force plate. You will be informed when you have reached the desired force level with the sound of a bell. The handle will be set in four randomized positions. These positions are comprised of two heights (belly height, and shoulder height) as well as at two reaches (80 percent of maximum reach and 110 percent of maximum reach). For each of the 4 hand positions, there will be up to 3 different exertion directions (push, pull and down). A very intuitive computer program will aid you in making sure you are pulling or pushing in the appropriate direction. Each effort will last for 1-3 seconds.

In total, approximately 48 exertions will be completed during the study. The entire protocol will occur in one, 2-hour testing sessions.

On a separate day proceeding to the experimental trial, you will come in to complete a standardized strength testing protocol. Strength testing will be completed using the biodex machine. The biodex is an isokinetic dynamometer, a piece of equipment that will provide resistance to your movement. In the case of this study, it will resist against arm flexion/extension, adduction/abduction and trunk flexion/extension. During the strength testing protocols, your body will be secured. While seated in the Biodex, you will be asked to perform two 3-second maximum voluntary efforts (MVE) with two minutes of rest in between, in each of the testing motions. During all of the MVE’s you will be asked to push as hard as you can against the appropriate biodex attachment.

Potential Harms, Risks or Discomforts:
The conditions and trials will occur within a fairly short time frame, and participants may experience some mild fatigue in the arm but this should be no more than would be experienced after any unaccustomed physical activity. If you feel tired or experience any discomfort, you can take a break or stop the testing. Personal information will be kept confidential, however if you are uncomfortable with providing personal information such as weight, age, etc., you may choose not to participate in this study.

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

Payment or Reimbursement:
Participants will be reimbursed with a $5 Tim Hortons card for each data collection session. The study will involve two data collections each one will be no longer than 60 minutes.

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

record the movement of the reflective markers so the subjects' confidentiality will be maintained.

Participation:
Your participation in this study is strictly voluntary. If you choose to volunteer, you have the right to withdraw from the study without any consequence at any time either before or during the testing sessions. If you choose to withdraw, all of your digital data will be permanently deleted from the computers and all paperwork will be shredded.

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

Information about Participating as a Study Subject:
If you have questions or require more information about the study itself, please contact Kayla Fewster.

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

McMaster Research Ethics Board Secretariat
Telephone: (905) 525-9140 ext. 23142
c/o Office of Research Services
E-mail: ethicsoffice@mcmaster.ca

CONSENT

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

____

Name of Participant

Appendix C:

The specific locations and placements of the 52-infared markers that were attached to the participants. These are the same locations used by Ford Motor Company, in order to drive Jack software within the Motion Analysis system.

1. Top Head	2. Back Head	3. Front Head
4. Left Head Offset	5. Right Back Head	6. Right Shoulder
7. Left Shoulder	8. Neck	9. Sternum
10. Left Back Offset	11. Right Back Offset	12. Right Bicep
13. Right Elbow	14. Right Posterior Elbow	15. Right Fore Arm
16. Right Radius	17. Right Ulna	18. Right Thumb
19. Right Hand	20. Right Pinky	21. Left Bicep
22. Left Elbow	23. Left Posterior Elbow	24. Left Forearm
25. Left Radius	26. Left Ulna	27. Left Thumb
28. Left Hand	29. Left Pinky	30. Right ASIS
31. Left ASIS	32. Right PSIS	33. Left PSIS
34. V Sacral	35. Right Hip	36. Left Hip
37. Right Thigh	38. Right Lateral Thigh	39. Right Knee
40. Right Shank	41. Right Ankle	42. Right Heel
43. Right Toe	44. Right Foot	45. Left Thigh
46. Left Lateral Thigh	47. Left Knee	48. Left Shank
49. Left Ankle	50. Left Toe	51. Left Heel
52. Left Foot		

Appendix D: Average Leaning Hand Resultant Force and Height for Each Separate Leaning Condition

	High Height						High Height					
	Long Reach						Short Reach					
	Down		Push		Pull		Down		Push		Pull	
	Low Force (27.5 N)	High Force (55 N)	Low Force (27.5 N)	High Force (55 N)	Low Force (27.5 N)	High Force (55 N)	Low Force (27.5 N)	High Force (55 N)	Low Force (27.5 N)	High Force (55 N)	Low Force (27.5 N)	High Force (55 N)
Leaning Hand Height	1.14	1.13	1.12	1.11	1.17	1.21	1.03	1.04	1.14	1.11	1.13	1.15
Leaning Hand Resultant Force	24.3	27.1	19.3	14.5	52.7	79.6	20.6	17.7	13.8	15.6	33.2	54.4

	Low Height						Low Height					
	Long Reach						Short Reach					
	Down		Push		Pull		Down		Push		Pull	
	Low Force (27.5 N)	High Force (55 N)	Low Force (27.5 N)	High Force (55 N)	Low Force (27.5 N)	High Force (55 N)	Low Force (27.5 N)	High Force (55 N)	Low Force (27.5 N)	High Force (55 N)	Low Force (27.5 N)	High Force (55 N)
Leaning Hand Height	1.09	1.06	1.09	1.11	1.11	1.13	1.03	1.01	1.05	1.08	1.11	1.12
Leaning Hand Resultant Force	28.3	25.0	52.7	70.3	30.5	25.5	19.5	22.3	31.0	53.0	20.7	20.3

	High Height						High Height					
	Long Reach						Short Reach					
	Down		Push		Pull		Down		Push		Pull	
SD Leaning Hand Height	201.0	212.4	181.8	225.2	160.4	114.5	226.3	329.4	189.1	204.6	204.4	174.7
SD Leaning Hand Force	13.1	18.9	11.0	7.4	20.4	22.4	12.5	9.7	7.7	11.7	17.2	24.2

	Low Height						Low Height					
	Long Reach						Short Reach					
	Down		Push		Pull		Down		Push		Pull	
SD Leaning Hand Height	173.1	180.6	153.0	140.9	162.9	148.8	194.8	201.6	178.5	167.9	168.3	157.5
SD Leaning Hand Force	17.5	15.5	18.5	23.0	11.5	13.2	8.7	11.4	14.2	20.4	14.3	12.0