AN INVESTIGATION OF EXTERNAL SUPPORT CHOICES AND BEHAVIOURS DURING ONE-HANDED EXERTIONS WITH CONSTRAINED REACHES

AN INVESTIGATION OF EXTERNAL SUPPORT CHOICES AND BEHAVIOURS DURING ONE-HANDED EXERTIONS WITH CONSTRAINED REACHES

By

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ABSTRACT

Introduction: External support behaviours, which include leaning (supporting with the non-task hand) or bracing (supporting with the body), are frequently employed by workers in manufacturing settings. However, current ergonomic assessment tools are limited by our limited understanding of these behaviours. Recent studies have investigated these behaviours, however, the designs of these studies are limited in their applicability to real-world scenarios. The purpose of this study was to assess how different task parameters affect the prediction of external support behaviours, as well as the effect of support on task hand, and body, kinematics and kinetics, in a minimally constrained experimental design. **Methods:** Female participants (n = 18) performed a series of one-handed maximal exertions (in the six orthogonal directions), and one precision task, in four hand Locations. Trials either featured support (as chosen by the participant), or no support. **Results & Discussion:** Three logistic regression models were developed, with inputs from individual and task characteristics, and they correctly predicted the occurrence of leaning, bracing, or simultaneous leaning and bracing, 74-86% of the time. Leaning and/or bracing were found to provide: 1) oppositional forces to increase task hand force generation, 2) balance, by countering destabilizing moments about the feet, and 3) a reduction in moment arm of the task hand force, with respect to the upper body joints, by bringing the shoulder closer to the task hand. Participants were able to exert 64.8% more force at the task hand as a result of support. Leaning hand placement depended on the task force direction and location. However, the positioning of the leaning hand varied very little. Finally, the precision condition showed that fine motor demands may also affect external support choice.

ACKNOWLEDGEMENTS

To my supervisor, Dr. Jim Potvin: One of the pivotal moments of my life was when I decided to send you an email one day. Since then, my life has been led down a better path, for which I will be forever grateful. I've learned invaluable lessons, whether academic, professional, or personal in nature, which will undoubtedly benefit me in the future to be less … you know. Something can truly be said about the benefits of external support, outside the contexts of biomechanics or ergonomics.

To my McMaster Occupational Biomechanics Labmates: When I started grad school, I was told it would be one of the best times of my life. I quickly realized that being around all of you would make that so very true. Where else is there this kind of concentration of awesome people? I can only hope that my future work environments foster the same kind of relationships that I have with each of you unique and wonderful characters.

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To my loved ones: You made me who I am and keep my wheels turning. Mom and Dad, your wallets are not the only thing I appreciate. Mom, your life is as inspiring as any story I know. Dad, you are the jack of all trades I can only aspire to be. Alicia, Ryan, and Michael, you each continue to do things that are remarkable in their own way. Finally, to my best friend Lindsey, you get me more than anyone in the world. I couldn't imagine who I'd be, or what I'd be doing, without you. I am not perfect, but I'm glad one of us is. **I mean it, thank you all.**

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1.0 INTRODUCTION

Work-related musculoskeletal disorders (WMSDs) are costly for both companies and their employees alike. While companies must bear the financial costs of lost time, productivity, employee compensation and job redesign, it is even more costly for employees whose lives and well-being are affected both at work and home. These injuries are often a consequence of poor ergonomic job design and unresolved ergonomic hazards, which employees endure as part of their work demands. In 2012 alone, 55,525 lost time injury claims were filed in Ontario (Workplace Safety Insurance Board, 2013). WMSDs are particularly prevalent in manufacturing environments, such as an automotive assembly line, where prolonged, non-optimal postures and repetitive high loading can often place a severe burden on workers. In Ontario, overexertion was reported to be the leading cause of workplace injury, accounting for about 18-19% of all injuries in 2012 (Workplace Safety Insurance Board, 2013). Meanwhile, in the U.S., the manufacturing industry accounted for one of the highest injury incidence rates in all private industry in 2011 and 2012, with 40.8 and 38.6 incidences per 10,000 full-time workers, respectively (US Department of Labor, 2012 & 2013). In particular, the automotive manufacturing industry in Ontario reports a high number of injury claims every year (1,897 total claims in 2012, or 4.4% of all claims) (Workplace Safety Insurance Board, 2013). While there has been a decrease in the number of claims in the automotive industry over the last decade, it is still important to maintain this trend by continuing to improve the workplace interventions for injury prevention.

Over the past few decades, automotive manufacturers have established ergonomics engineering programs in an effort to reduce WMSDs and their associated costs. Conventionally, ergonomic intervention programs will react to injury claims by assessing “at-risk” jobs and aiding in the redesign process. However, the major aim of these newer programs is to improve the proactive job design process, by ensuring that the majority of employees are able to perform the jobs with a low risk of WMSDs. By doing so, companies can not only ensure the feasibility of assembly jobs before they exist, but they can also help prevent injuries and, thus, reduce the cost of injury and job redesign before the issue is raised (Chaffin, 2002). This proactive approach is a cost effective way to improve manufacturing engineering efficiency and preventing injuries (Figure 1).

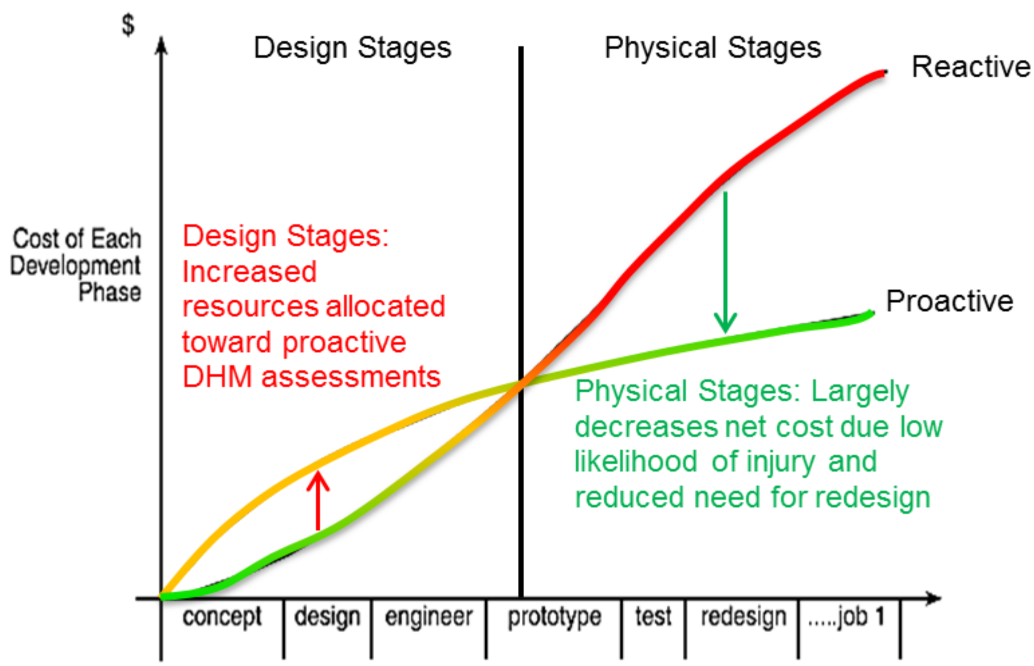


Figure 1: The two curves on this graph represent the cost time-history of two manufacturing design approaches: 1) the traditional serial process, where workers are inserted into physical work environments without ensuring ergonomic feasibility, and 2) computer aided evaluation (CAE) / digital mock-up (DMU) processes, where jobs are proactively designed in a virtual environment and evaluated for ergonomic feasibility (adapted from Chaffin, 2002).

Ergonomic engineering teams have employed digital human models (DHMs) as the primary method for proactive ergonomic job analyses. Software programs such as Jack Static Strength Prediction (Siemens Corporation, Ann Arbor, MI), 3D Static Strength Prediction (University of Michigan, Ann Arbor, MI), and Santos (University of Iowa, Iowa City, IA), allow users to insert a digital human manikin within a virtual work environment, and manipulate its posture to those assumed to be associated with performing various work tasks. By doing so, ergonomists can assess the feasibility of reach, clearance, line of sight, and joint loading based on the physical constraints and load demands of the task. The external work environment can be created with CAD files representing features such as tools, parts, or entire vehicles, while the manikin can be customized for both gender and anthropometry. For the manikin, the standard procedure is to use the anthropometry of a 50th percentile female and to ensure joint strength demands are acceptable for 75% of the female population (i.e. 25th percentile or “weak female”). By ensuring a weak female is capable of performing a task, ergonomists can assume that the vast majority of the worker population will be able to perform the task within acceptable limits of joint demands and reach.

While DHMs are prominent tools for work assessments, between-user variability is an issue because there is no standard method for the manipulation of the manikins within a given work environment (Chaffin, 2002). For the most part, ergonomists will arbitrarily manipulate a manikin’s posture, based on either photos of an existing job or instinctive construct, so that it appears “natural” when performing a task. This method may be an issue particularly in today’s world of globally common manufacturing processes, where it is entirely possible for two different ergonomic engineering teams to assess the same job, using the same DHM software, and come to drastically conflicting conclusions of job’s acceptability. This is due, in part, to the sensitivity of these DHM models. It has been shown that estimates of joint strength are extremely sensitive to minor variations in joint angles (Chaffin & Erig, 1991). In other words, if an ergonomist manipulates a manikin slightly, there may be a drastic increase or decrease in force limits compared to an assessment performed by another user. In an attempt to solve the between-user discrepancy, posture prediction methods have been developed, which is a feature currently available in various DHM programs (Fewster, 2013). By automatically predicting the manikin’s full body posture, based on user-inputted hand locations and force directions, posture prediction has provided a positive alternative to the arbitrary manual method. Up to this point, however, posture prediction algorithms do not yet have the ability to account for external support behaviours and their influence on posture.

External support behaviours are very common while performing tasks with the hand in occupational settings (Cappelletto et al., 2012; Godin et al., 2008; Jones et al, 2008). External support involves the use of one or more body parts to support the body while a task is being performed. In work environments, such as in automotive assembly, the abundance of kinematic work constraints creates a welcoming environment for external support behaviours. As expected, high rates of these behaviours have been reported in previous surveys of assembly worker behaviours in automotive manufacturing plants (Cappelletto et al., 2012; Jones et al., 2008). These work constraints can include: the frame of the vehicle (such as the A and B pillars), front fenders, front or rear fascia, the engine, or interior features such as the seats and floor pan.

Previous studies provide insight into why external support behaviours may be beneficial to employees. Jones et al. (2013) showed that the use of external support can significantly increase the maximum force capability of the task hand by an average 43%, by creating oppositional forces to the task force direction with the leaning hand or bracing body region. Cappelletto (2013) and Fewster (2013) found that, when external bracing or leaning was used at the thighs and hands, respectively, it caused an increase in the participants' ability to move their centre of gravity forward without losing balance. Without the external support, participants would need to maintain stability by moving their body center of gravity posteriorly (Cappelletto, 2013; Kingma & van Dieën, 2004). In short, external support essentially increases the functional reach distance of the participant. The wider support base also allows participants to get their shoulder closer to the task element, effectively increasing the number of postures the participant can attain. With this benefit, participants may be able to increase the strength capability at the shoulder by optimizing their position and posture for a given task, in effect decreasing the risk of injury (Cappelletto, 2013). It has also been shown that bracing at the trunk can significantly decrease trunk extensor muscle activity during both lifts and prolonged static trunk flexion postures (Damecour et al., 2009, 2011; Ferguson et al., 2002). A decrease in moment demands about the spine, due to extensor moments caused by the external support surfaces acting on the upper body, has also been discussed as a benefit associated with leaning and bracing in past literature (Cappelletto, 2013; Fewster, 2013; Kingma and van Dieën, 2004).

Despite the high incidence rate of external support behaviours, most conventional ergonomic tools have ignored them. For example, tools for evaluating lifts, such as the NIOSH lifting equation (Waters et al., 1993) and the Liberty Mutual tables for manual materials handling (Snook & Ciriello, 1991), assume that lifts are performed with two hands free from external support contributions (Ferguson et al., 2002). For biomechanical linked segment modelling, incorporating external support forces are impossible to compute during one-handed tasks because of the statically indeterminate system created by the second external force (Jones et al., 2008). Therefore, external support forces must be estimated or directly measured (Howard et al., 2012). The Jack Static Strength Prediction DHM (Siemens Corporation, Ann Arbor, MI) has attempted to include support behaviours in their analysis modules (Chiang et al., 2006). However, the algorithms used were based purely on assumptions not supported by any behavioural or biomechanical research and are limited to two-handed tasks (Fewster, 2013; Jones et al., 2008). It is clear that, until very recently, insufficient research exists to provide adequate understanding of the kinetic and kinematic implications of external support, such as the likely location and magnitudes of external support forces, as well as the implications for joint loading (Jones et al., 2008). Thus, it has been impossible for ergonomists to accurately account for leaning or bracing in their work assessments when using DHMs.

It is apparent that, when assembling a motor vehicle, many jobs require an element of precision. Examples can include: hand-starting a nut onto a stud, locating a tool spindle socket over a stud, or feeding a cable through a tight space and seating it onto a connector. While past surveys of automotive assembly lines outlined many of the parameters of jobs that involved external support (Cappelletto et al., 2012; Jones et al., 2008), they did not report on the precision requirements of the task element, instead assuming all tasks were gross force applications exerted in a nominal force direction. Recently, there has been an increase in experimental research investigating external support (Cappelletto, 2013; Fewster, 2013; Jones et al., 2013), but all studies thus far have only focused on gross motor tasks at the task hand when performing lab-based experiments. As a novel feature in this thesis, I investigated the effect of fine motor tasks, i.e. hand tasks involving small movements or targets with high precision demand, on external support behaviours. This postulation was based on both biomechanical and cognitive theory and are discussed further in 2.6 External Support and Fine Motor High Precision Tasks. In summary, however, external support may be used by employees to: 1) increase both bodily comfort while performing the precise task, and/or 2) improve the accuracy of the task by: i) increasing the postural stability of the bodily system by anchoring it to a solid object, and/or ii) decreasing the cognitive load on the central nervous system by restricting the degrees of freedom of the body's movement. It is important to add that this may also apply, to a lesser extent, to gross motor tasks.

In Figure 2, Jones (2011) presented a series that factors that were hypothesized to influence external support behaviours during one-handed tasks, and she classified these factors into biomechanical constraints, task constraints, and individual factors. However, the precision of the motor tasks was not considered as a task factor. For part of this study, I attempted to determine if precision tasks are a significant predictor of these behaviours.

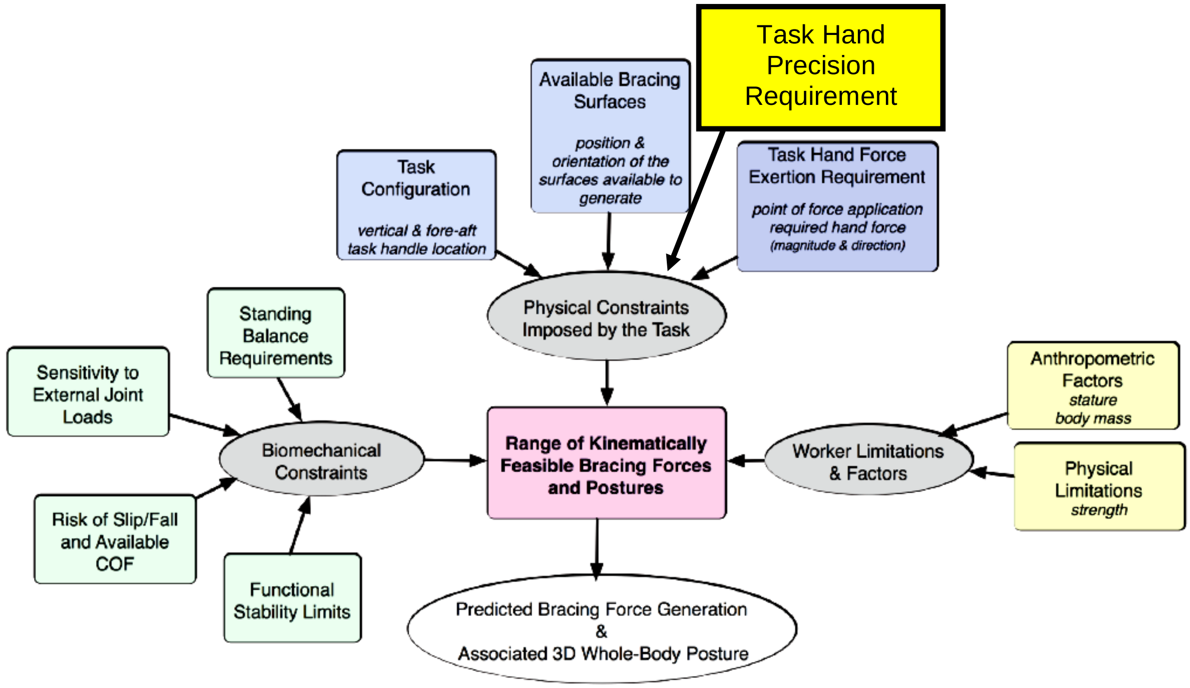


Figure 2: Adapted from Jones (2011), showing all the factors that were hypothesized to influence external support behaviours. For an additional analysis, this thesis will determine if task precision (yellow box) also belongs somewhere in this figure as a significant predictor of these behaviours.

As discussed previously, accurate posture prediction, in DHM software programs, is an essential step to improving the fidelity of ergonomic work assessments. As stated by Chaffin (2005), experimental posture collection is the best way to acquire data when creating models for posture prediction. Collecting empirical data allows us to gain a consistent understanding of joint segment biomechanics and choice behaviours based on a variety of factors including anthropometry, strength, and task characteristics, etc. Thus, a second novel aspect in this thesis was to introduce the choice of each of leaning and/or bracing with the freedom to adjust stance. Recent external support studies have included a choice element for leaning only (Fewster, 2013), bracing only (Cappelletto, 2013), or stance (Jones, 2011), however, this study was the first to not constrain any of the three for any given trial. By introducing this freedom of choice, alongside adding fine motor tasks as another variable, this dissertation provides more valuable information regarding when and why people choose to externally support. I also aimed to represent task parameters close to those commonly seen in automotive assembly so that the prediction model created from these data will best reflect the jobs in industry.

1.1 Statement of Purpose

The purpose of this study was to investigate external support behaviours when performing both gross and fine motor tasks in a kinematically constrained reaching environment. These external support behaviours included both leaning (with the contralateral hand) and bracing (at the thighs). The parameters to be tested included: external support presence, task hand location, task type (fine and gross motor tasks), and force direction (for gross motor tasks). The specific goals of this study included the following:

1. To develop a model that is able to predict when and how external support is used, as well as determine the significant predictors of these behaviours.
2. To compare changes in joint kinetic and kinematic characteristics when performing tasks in the various experimental conditions.
3. To compare the external support and task hand force magnitudes, directions and locations under the various experimental conditions.

Compared to previous external support studies, the postures tested in this thesis were performed in an environment with more available external support surfaces (in number and in size), fewer constraints on external support and stance choices, and introduced precision motor tasks as another task variable. The long term goal of the outcomes from this thesis is to provide DHM software packages with a new library of postures and data to improve the prediction of external support behaviours. This will ultimately serve to providing ergonomists with improved, accurate and reliable tools for evaluating work postures that involve external support.

1.2 Hypotheses

I hypothesized that the following observations will be made from this experiment:

1. External support would be employed by participants, for the majority of the maximum effort conditions. The expected high prevalence of these behaviours would be a consequence of a variety of factors:
    a. To generate oppositional forces to maximize forces at the task hand.
    b. To minimize critical joint moments, including the trunk, shoulder and elbow.
    c. To translate the centre of gravity forward, to get closer to the task hand element and maintain balance throughout the exertion.
2. For conditions where external support is utilized, task hand force would significantly exceed forces associated with no external support, with the exception of "inferior" and "anterior" task hand exertions.
3. Significant predictors of external support behaviours would be the task hand force direction, vertical and horizontal task hand location, and participant shoulder and trunk strengths.
4. For the fine motor (i.e. "precision") task condition, external support would also be utilized in the majority of trials. Longer horizontal reaches will result in greater prevalence of external support, while trials with external support will result in improved task performance, as defined by decreased task completion time.

2.0 LITERATURE REVIEW

2.1 External Support Behaviours in Industry

Before conducting any lab-based experiments with external support, it is important to quantify and understand the behaviours that exist in industry so that experimental trials can best reflect real-life scenarios. To do so, in-plant surveys have been performed at various automotive assembly plants. Jones et al. (2008) analyzed 910 samples of video from 20 total jobs at two different automotive assembly plants. Each of these jobs was selected to represent the diverse array of jobs around the plant. Three different workers were recorded performing each job for an average of about six cycles. Of the 910 instances of work elements, 48% (436 total) were found to involve external support. A categorical analysis on a wide variety of job parameters including; behaviours (e.g. support hand (L or R), external bracing body part, hand grip posture), vehicle point of contact, as well as body segment angles based on a commonly used static posture binning checklist (McAtamney & Cortlett, 1993), was performed for each of the 436 external support instances. In the interest of my thesis, 50% of incidences involving one-handed task exertions involved the use of the contralateral hand for leaning support. Furthermore, 88% of all incidences analyzed in Jones et al. (2008) involved at least one secondary external bracing point in addition to contralateral hand leaning; the most common secondary points were the lower body regions (e.g. pelvis, abdomen, and thighs). While their survey did include the determination of body segment angles, its generalizability was limited because they analyzed only a limited selection of jobs at the assembly plants. Also, they did not report the precise heights, reaches and exertion directions for each task element. This was an important omission as it could have provided insight regarding whether these variables had an influence on external support behaviours.

The checklist used by Jones et al (2008) became the basis for a more comprehensive survey by Cappelletto et al. (2012), who observed every workstation (n = 250) in the final assembly area of Ford's Oakville Assembly Plant in Oakville, ON, using an in-person checklist method. From these workstations, a total of 613 task elements were surveyed. Aside from their limited postural measures (only trunk postures were observed), Cappelletto et al. (2012) provided a much more inclusive report in comparison to Jones et al. (2008). In particular, both task hand force direction and task hand location (in the vertical plane) were reported. Cappelletto et al. (2012) found that 101 of the 250 workstations (40%), and 363 of 613 (59%) of the task elements, involved at least one external support behaviour. Of these workstations, 78% involved one-handed task hand exertions and, of those, 67% involved leaning only, 26% involved combined leaning and bracing, and 6% involved bracing only (Figure 3). For the task hand, a relatively even distribution was found for force direction, with the most common being up (25%) and the least common being pull (11%) (Figure 4). The most common grip type was a power grip (37%). For the leaning hand (Figure 5), the most common force directions were push forward (53%) and down (35%), while the most common grip types were flat press (61%) and closed fist palm press (26%). The experimental setup, used in my thesis, attempted to create an environment where these force direction and grip conditions will be dictated.

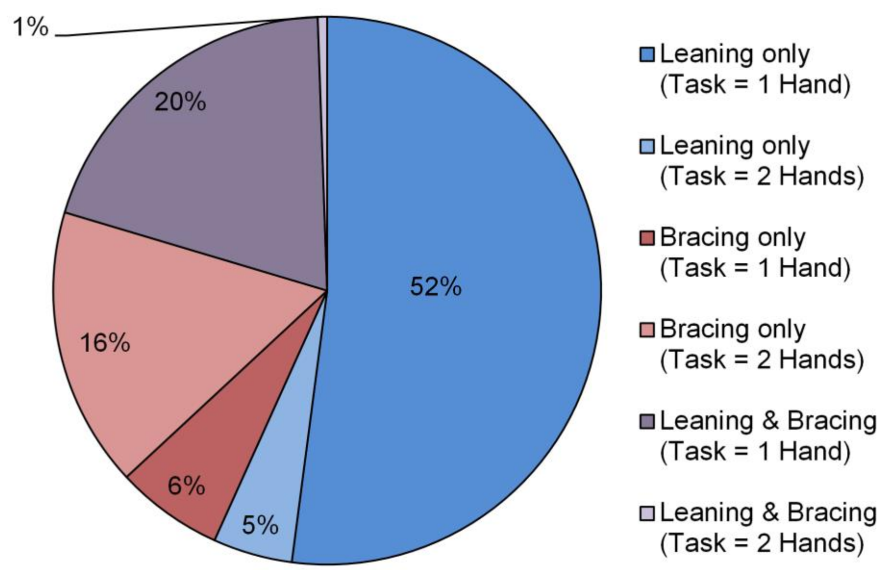


Figure 3: Frequencies of external support behaviours, sorted by number of hands used to perform the task element (i.e. one- or two-handed tasks) (Cappelletto et al., 2012).

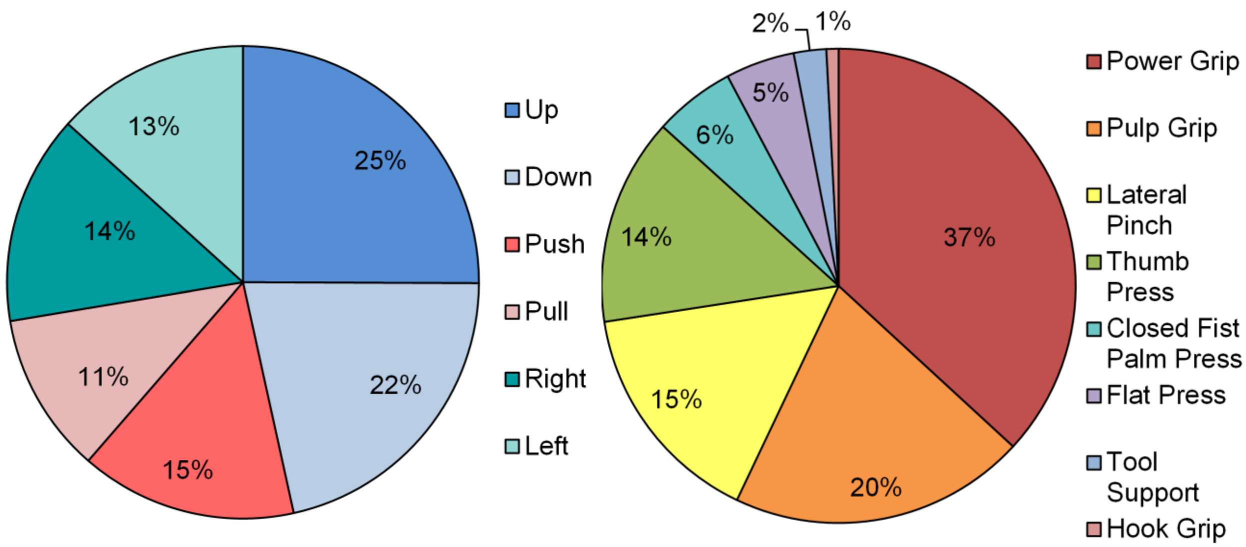


Figure 4: Frequencies of task hand force direction (left) and task hand grip types (right) (Cappelletto et al., 2012).

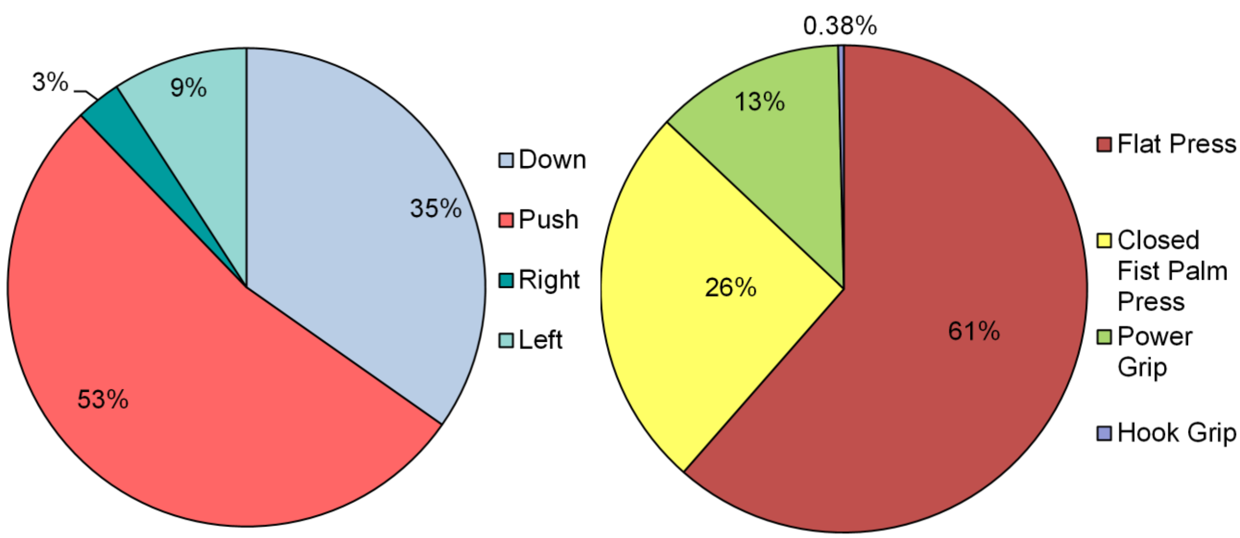


Figure 5: Frequencies of leaning hand force direction (left) and leaning hand grip types (right) (Cappelletto et al., 2012).

Cappelletto et al. (2008) also showed the distribution of leaning and bracing heights (Figure 6). They reported a high occurrence of both leaning and bracing between the knee and pelvis, and a very high occurrence of leaning above the shoulder. Once again, my experimental setup was designed to best emulate the common heights from the Cappelletto et al. (2012) survey in my experimental setup.

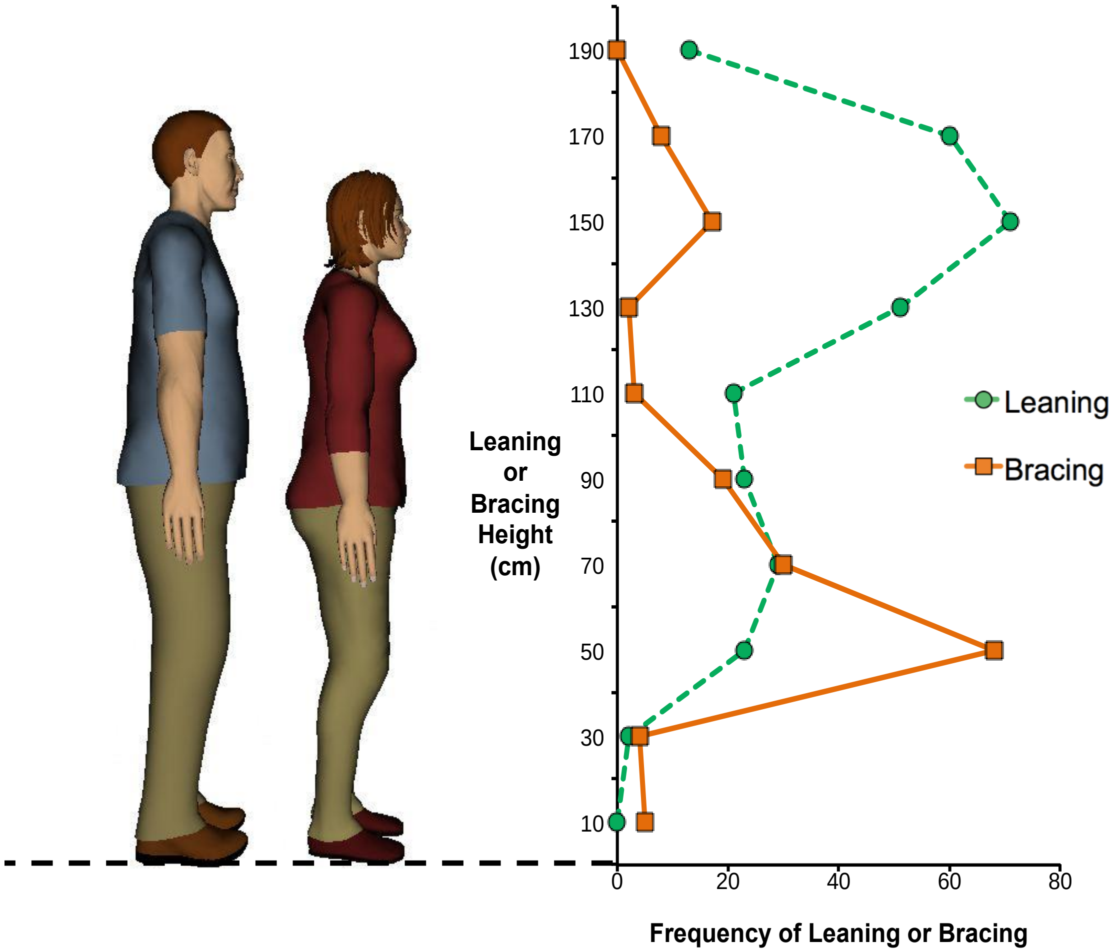


Figure 6: This graph shows the frequency distribution of leaning and bracing behaviours from an automotive assembly plant survey relative to 50th percentile male and 50th percentile female manikins (Cappelletto et al., 2012). The 101 workstations, with external support, included 94 males and 7 females.

2.2 Biomechanical Effects of External Support Behaviours

Biomechanical investigations of external support behaviours have rarely been performed. However, from those studies there have been some consistently reported effects. The first consistent finding is that the incorporation of external support can significantly reduce low-back loading (Ferguson et al., 2002; Lardi & Frazer, 2003; Kingma & van Dieën, 2004; Damecour et al., 2009 & 2012). Ferguson et al. (2002) used an EMG-assisted modelling technique to estimate three loads on the low back: compression, anterior-posterior shear, and lateral shear.

Of the one-handed task conditions, those that incorporated the contralateral support hand reduced low back loading measures by a minimum of 15% compared to conditions without the leaning hand. More detailed results showed a decrease in all three measures of lower back loading whenever there was a support hand present. Kingma & van Dieën (2004) also investigated the effect of a support hand during one-handed load lifts, using a similar estimation method as Ferguson et al. (2002), and measured the net resultant moment at the L5/S1 joint. The results showed that incorporating a support hand reduces the net lumbar moment by 30% during one-handed tasks. Lardi & Frazer (2003) applied a leaning hand force to a load cell while performing bolt fastening with the task hand, and estimated compression at the L4/L5 joint using a linked segment model. The support hand decreased L4/L5 compression by approximately 1000 N. In the context of body bracing, a similar trend was observed. One research group performed two different studies (Damecour et al., 2009 & 2012) that estimated muscle force, based on EMG of various upper and lower trunk muscles and the hamstrings. Participants performed prolonged box holds above a table with either no bracing, bracing at the pelvis (using the edge of the table) or with a customized chest brace. In the first study, Damecour et al. (2009) reported a 60% decrease in extensor muscle activity when using the chest brace, while the pelvic bracing had no effect on lower back muscle activity. In the second study, Damecour et al. (2012) introduced dynamic axial twists during a box lifting task, and found a similar trend; a 23-30% reduction in trunk extensor activity.

A second consistent finding is that the use of external support can increase one's force generating capacity at the hand. Multiple studies have reported that the maximum force generating capacity is dependent on the availability of reaction forces available to the participant (Kroemer & Robinson, 1971; Kroemer, 1974). Other studies also noted that force generation capability was higher when a support hand was placed on an available surface, such as a wall (Pheasant et al., 1982), or even a rigid part of their own body (Haslegrave et al., 1997). Jones et al. (2013) found that external support surfaces, at the thighs, allowed participants to generate an average of 43% more manual arm force compared to non-supported trials. They suggested that forces, in opposition to those at the task hand, allowed for a greater force generating capacity.

In addition to the reduction in low back loading, and the increase in task hand force generation capability, there have also been some consistent kinematic trends related to postural adaptations. Damecour et al. (2012) found that hip bracing decreased trunk flexion when performing a box hold over a desk. Since there was no external support, there was a need to employ a "hip-balance strategy," in which participants shifted their centre of mass backwards to counter the forward shifting caused by the reach. Cappelletto (2013) noticed the same effect while observing trials of submaximal force exertions with constrained reaching. She reported that, similar to Damecour et al. (2012), the bracing surface at the thighs/pelvis allowed the participants to move their centre of gravity forward, reducing their reach to the task element. This reach capability allowed participants to obtain a wider range of postures and, thus, may have given them more of an opportunity to reduce the moment arm at the task hand shoulder, and effectively increase the maximum force that would be acceptable at the hand. In Cappelletto (2013), conditions without external bracing had greater trunk flexion angles; greater forward flexion angles at the shoulder and more extended elbow angles, since there was a need to shift the hips back to maintain balance. Secondly, the use of external support during one-handed exertions, seemed to have an influence on asymmetrical posturing at the trunk, causing trunk axial twist demands (Ferguson et al., 2002; Kingma & van Dieën, 2004). Cappelletto (2013) and Fewster (2013) both found that trunk twisting was used to get the shoulder of the task arm closer to the task element to increase the strength capability of the task arm. Overall, these studies found that external support strategies can improve balance, and force generation capability at the task arm, for participants performing hand force exertions. Fischer et al. (2013) noted that, depending on force direction, task hand force capacity can be limited by balance (for upward efforts) or joint strength (for downward efforts). External support strategies can improve balance (eliminating the hip-balance strategy) and/or joint strength (improving upper arm force generating capacity) and are, therefore, beneficial for tasks with hand force exertion demands.

Despite the aforementioned consistent findings, studies that quantified the force applied at the leaning hand have reported conflicting evidence. These studies have either shown that leaning hand forces are primarily applied for supporting body weight during tasks (Fewster, 2013; Godin et al., 2008; Lardi & Frazer, 2003), or for generating oppositional forces to the task hand (Jones, 2011). I argue that these conflicts may be dependent on many factors, including; a) task hand force level, and/or b) task hand force directions, compounded by the shape and orientation of the surfaces in the experiments.

Godin et al. (2008) simulated four minimally loaded, fine motor assembly tasks, varying in reach and height relative to the participant, which involved a leaning hand for external support. The researchers placed a load cell under the leaning hand for each task and the resultant force was reported as a percentage of body weight (%BW). The results showed leaning hand forces ranging from 5.5 to 12.1 %BW, and the farthest horizontal reach was associated with the largest mean hand force. Lardi & Frazer (2003) also tested participants as they performed minimal load tasks, and in various combinations of trunk flexion and arm forward flexion angles. The farthest trunk flexion and arm flexion angles were associated with the greatest leaning forces, which ranged between 10 to 15 %BW. Notably, the leaning hand forces increased when greater horizontal reaches were tested in both studies. The evidence from these studies indicates that leaning hand forces are applied at a relatively low magnitude, for supporting the body for tasks with minimal task hand load.

In a more recent study, Fewster (2013) tested gross motor task hand forces that were much higher than the two earlier studies (Godin et al., 2008; Lardi & Frazer, 2003). Fewster (2013) reported average leaning hand forces of 5.5±1.7% body weight, with the pull tasks associated with the highest forces at 8.9% body weight. Despite having greater task hand forces than Godin et al. (2008) and Lardi & Frazer (2003), Fewster (2013) reported the lowest leaning hand forces of all three studies. This can likely be explained by her experimental setup, where the primary leaning surface was in a vertical, (rather than horizontal) orientation. Unlike the horizontal surfaces from the other two studies, the vertical surface as in Fewster (2013) did not allow for participants to lean their upper body over the surface and apply a higher leaning force. To compound this further, the force directions used by Fewster (2013) were pull, down and push. At the task hand, down (i.e. inferior) and push (i.e. anterior) are not oppositional to the anterior force applied by the leaning hand into a vertical surface (i.e. oppositional would be a posterior pull). If one was to apply an anterior leaning force against a vertical surface, when performing push and down exertions at the task hand, there would be no benefit of oppositional force generation to achieve greater hand forces at the task hand (Kroemer & Robinson, 1971; Kroemer, 1974). Additionally, the anterior leaning hand force would not counteract the destabilizing forces induced by the push or down task hand exertions. Therefore, the discrepancy between Fewster (2013) and the two “minimal load” studies (Godin et al., 2008; Lardi & Frazer, 2003) shows that task hand force direction (compounded by experimental configuration) can influence leaning hand forces more than task hand force level.

In contrast to the three studies previously mentioned, Jones (2011) tested sub- and maximal gross motor task hand force exertions and found an increase in leaning hand forces that were associated with an increase in task hand forces. Based on this finding, she postulated that hand leaning forces are primarily generated for creating an oppositional force to the task hand. Since maximal task hand forces were tested, it is not surprising that high leaning hand forces would be observed to generate an oppositional force to the task hand, or to counteract destabilizing forces from the task hand. Furthermore, her experimental setup offered ideal surfaces for generating high forces with the leaning hand, in any direction (Section 2.3). Thus, Jones’s (2011) statement, that leaning hand forces are primarily for generating oppositional forces, is likely a consequence of both; a) the high force levels that were tested (maximal task hand forces being generated), and b) the ideal conditions in the setup to generate high oppositional forces with the leaning hand.

2.3 Protocols, Strengths & Limitations of Major External Support Studies

My thesis will focus and expand on three previous studies; Jones (2011), Cappelletto (2013), and Fewster (2013). Each selected conditions to reflect those most common in automotive assembly plants, with the ultimate goal of improving DHMs for ergonomic intervention in the automotive industry. Each study also observed the effects of some combination of task hand location, force direction and external support type on whole body kinematics and kinetics, as well as the external support force characteristics during one-handed gross motor tasks. All three studies also created a model using their data to predict external support behaviours (see sections 2.4 and 2.5). While many of the findings from those studies have already been discussed above, further detail regarding the experimental protocol will be discussed below. The task hand location conditions, as well as gross motor task force directions are summarized in Table 1.

Table 1: The top matrix outlines the conditions tested in past external support research; “J,” “F,” and “C” refer to conditions tested by Jones (2011), Fewster (2013), and Cappelletto (2013) studies, respectively. The upper table shows the task hand height, task hand reach, and force directions for gross motor tasks.

		Force Direction					
Task Hand Height	Task Hand Reach	Superior	Inferior	Anterior	Posterior	Lateral	Medial
High: ≥70% Stature	Close: 60%AL			J	J	J	J
	Medium: 90%AL		F	F	F		
	Far: >110%AL		F	F	F		
Medium: <70%, >50% Stature	Close: 60%AL	J		J	J	J	J
	Medium: 90%AL	C	C, F	F	C, F		
	Far: >110%AL	C, J	C, F	F, J	C, F, J	J	J
Low: ≤50% Stature	Close: 60%AL	J		J	J	J	J
	Medium: 90%AL	C	C		C		
	Far: >110%AL	C	C		C		

		Cappelletto (2013)	Fewster (2013)	Jones (2012)
External Support	Leaning Only		✓	✓
	Bracing Only	✓		✓
	Leaning and Bracing			✓
	Choice: Leaning and/or Bracing			
	None	✓	✓	✓
Force Level	Maximal			✓
	Submaximal	✓	✓	
	Precision			
Available Surfaces	Vertical Hip/Thigh Bracing	✓		✓
	Horizontal Hand Leaning		✓	✓
	Vertical Hand Leaning		✓	
Stance	Constrained	✓	✓	
	Unconstrained			✓

Cappelletto (2013) observed 20 female participants performing one-handed constrained reaches to task elements at four different locations. An external bracing surface was provided at the thighs, and the participants were asked to perform submaximal gross motor force exertions on a handle attached to a load cell. Two submaximal force levels (27.5 N and 55 N) were performed in each condition, while force directions included up, down and push. A trial was only considered to be successful if at least 90% of the resultant task hand force was in the required direction for a given trial. Participant strength and anthropometrics were also collected, to be used for further analyses. For the first set of trials, the participants were given the option to brace when performing the task, but were not explicitly instructed to brace. For the second set of trials, participants were instructed to use the opposite strategy observed in the corresponding condition in the first set (see Figure 7). This way, the researcher obtained “bracing choice” data while having an equal number of trials, with and without bracing, for statistical comparisons of other variables.

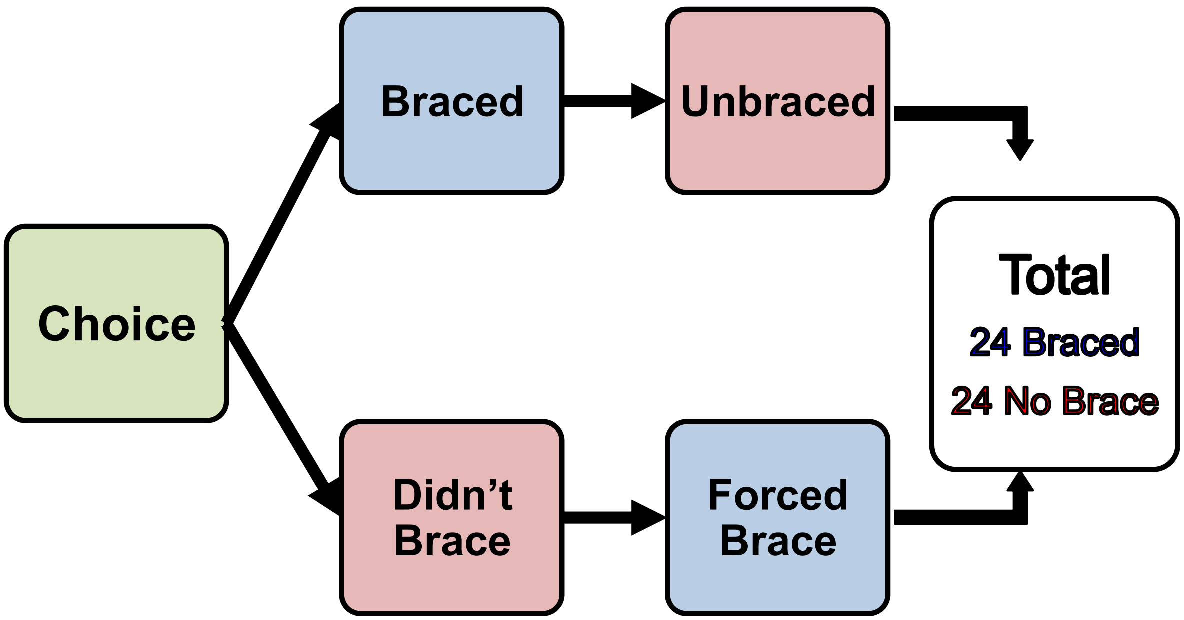


Figure 7: Trial conditions in Cappelletto (2013), showing the order in which braced vs. unbraced trials were performed.

Fewster (2013) performed a similar experimental protocol for her study, however the main difference was that leaning with the contralateral hand was the focal point, not lower body bracing. Like Cappelletto (2013), 20 females participated in the study while strength and anthropometrics were also collected. Furthermore, four task hand locations, two levels submaximal gross motor force exertions (27.5 and 55 N), and two conditions of support surface availability were the independent variables in the experimental conditions. These conditions were performed in similar order to Cappelletto (2013), where participants were given the option to lean in the first set of trials (Figure 7). In the setup, both a horizontal and vertical leaning surface was provided for the participants, which is conceptually very useful when attempting to determine participant choices/behaviours in a less constrained environment. The vertical surface was setup to very accurately simulate an A- or B-pillar of a vehicle, which are common locations for leaning (Cappelletto et al., 2012). However, one issue to note is that the majority of participants used only the vertical surface, despite the fact that, in industry, “down” is the most common force direction for the leaning hand (Cappelletto et al., 2012). This observation may have been due to limitations of the horizontal surface of the experimental setup.

The apparent preference to lean on the vertical surface likely occurred because the horizontal leaning surface was positioned laterally to the participant, and not centered underneath the trunk and shoulders (Figure 8). While it was not reported, using the horizontal surface may have caused a greater moment at the leaning shoulder and/or uncomfortable postures at the wrist and elbow. Participants may have preferred the vertical surface simply because it may have not been possible for participants to find a “comfortable” posture. This may have limited the applicability of the observed leaning behaviours to an automotive manufacturing environment. Also, like Cappelletto (2013), stance was constrained to an even, double stance, which could also have eliminated potentially more “natural” position that a participant may adopt in reality.

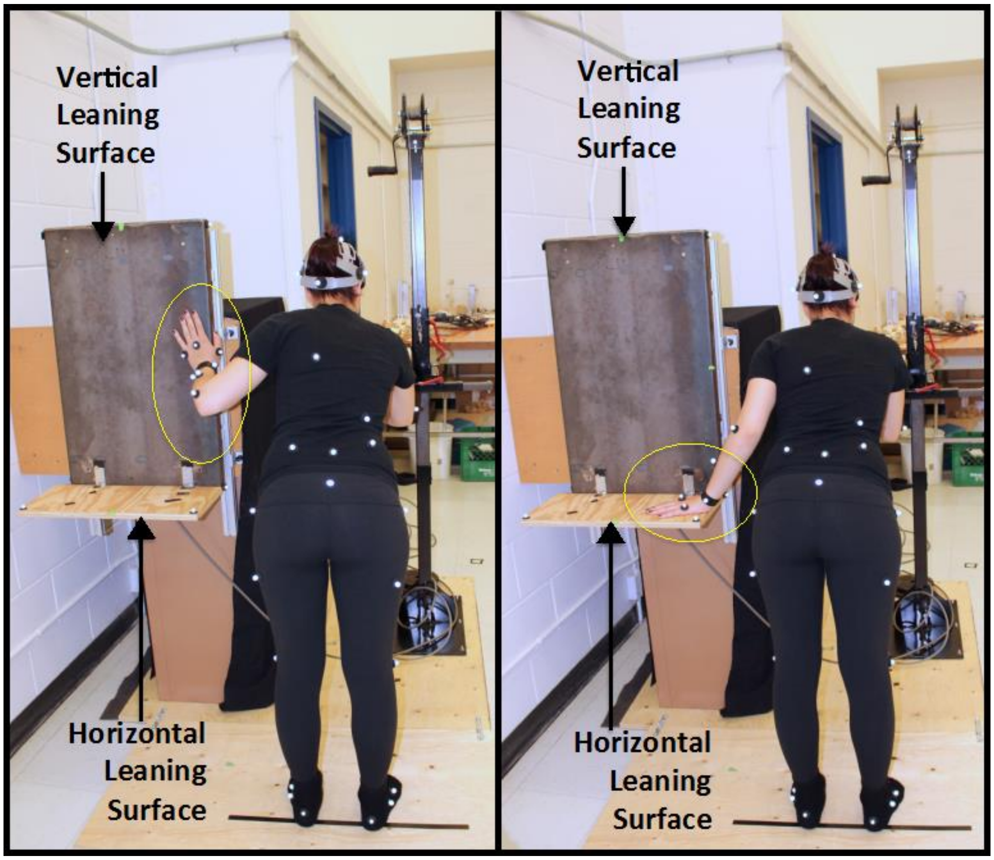


Figure 8: The two images above illustrate a sample participant demonstrating a one-handed reach accompanied with leaning using the vertical surface (left) or the horizontal surface (right) from Fewster (2013). The horizontal surface was rarely used, which is unreflective of workplace observations (Cappelletto et al., 2012). This is likely due to the lateral positioning of the horizontal surface, which likely required a greater moment at the leaning arm shoulder, and less comfortable joint postures, compared to use of the vertical surface. Note: I used a more centered surface for my thesis, with the expectation that the rate of leaning using the horizontal surface would increase.

Data processing was similar for both Cappelletto (2013) and Fewster (2013). Full body kinematic data were captured via a passive motion capture system. For all trials, the time frame at which the force met both the required direction (90% in the nominal direction) and magnitude criteria was selected for analysis. The static posture was synced with a manikin of equal anthropometrics in Jack 7.1 Static Strength Prediction Software (Siemens Corporation, Ann Arbor, MI) and joint kinematic and kinetic outputs were recorded for statistical analysis using the ForceSolver module.

Jones (2011) was the first to perform a large-scale experimental analysis of external support behaviours. She recruited 25 participants comprised of males and females. Standardized strength tests (including leg strength) were performed, followed by anthropometric measurements. For the task hand, 50% and 100% maximal force exertions were tested for a wide range of hand location and force direction conditions (see Table 1). Four external support conditions were also tested (no support, thigh bracing only, hand leaning only, and combined leaning and bracing). Before each trial, participants were informed regarding what support surfaces were available to them. An important feature of Jones (2011) was that maximal forces were tested in addition to submaximal forces; both Cappelletto (2013) and Fewster (2013) were limited to only submaximal forces. Currently, during proactive ergonomic simulations in industry, engineers want to know the maximum force limit for a given task. Once this force is known, parts can be designed with the optimal tradeoff between ease of assembly (insertion forces within the derived limit) and part quality (retention forces as high as possible). Thus, determining the maximum force at the task hand provides more beneficial information to automotive companies for design purposes. While the submaximal tasks may inform us of body kinematics patterns with external support, they do not provide us with the benefit of knowing the maximum force generating capability for a given task that incorporates external support. A final, unique strength of Jones (2011) was that participant stance was not constrained for any trials. This allowed participants to get in more natural postures for generating force and is, thus, more applicable to workplace scenarios, where stance is most often not constrained. Once again, when not constraining the whole body kinematics, data are more generalizable to workplace scenarios.

Despite the aforementioned strengths of Jones (2011), there were some notable limitations. In total, five nominal force exertion directions were tested in Jones (2011). However, unlike Fewster (2013) and Cappelletto (2013), Jones (2011) did not control for the resultant force direction to go in the direction of the nominal force. This limited the applicability of her results, since assembly tasks typically require a task hand force vector to be parallel to the required direction to be assembled properly (e.g. electrical connectors, hose insertions, etc.). Also, similar to Fewster (2013), Jones (2011) did not provide leaning hand surface(s) that satisfactorily reflect those available in automotive assembly. While the Jones (2011) hand leaning surface did allow for downward leaning hand forces that are reflective of industry (Cappelletto et al., 2012), the dimensions of the surface limited the postures of the participant (Figure 9). The hand leaning surface was a simple handrail that ran transversely to the participant, and was not an ideal setup for three reasons. First, it did not offer the participant a range of horizontal positions for their leaning hand, which limits the applicability of the data for posture prediction if the participant had no choice but to place their hand at only one horizontal location. Second, it elicited the use of a power grip for the leaning hand, which is unreflective of workplace hand postures (Cappelletto et al., 2012), and can allow for an unreasonably high reaction force capability at the leaning hand. Third, Jones (2011) provided no vertical leaning surface. To improve on this in my thesis experiment, I utilized a setup incorporating a vertical leaning surface similar to Fewster (2011), in addition to a horizontal surface that; a) offered a wide, flat horizontal and lateral area of for leaning arm positioning/posturing (similar to a floor pan of a vehicle), and b) was centered to the torso of the participant.

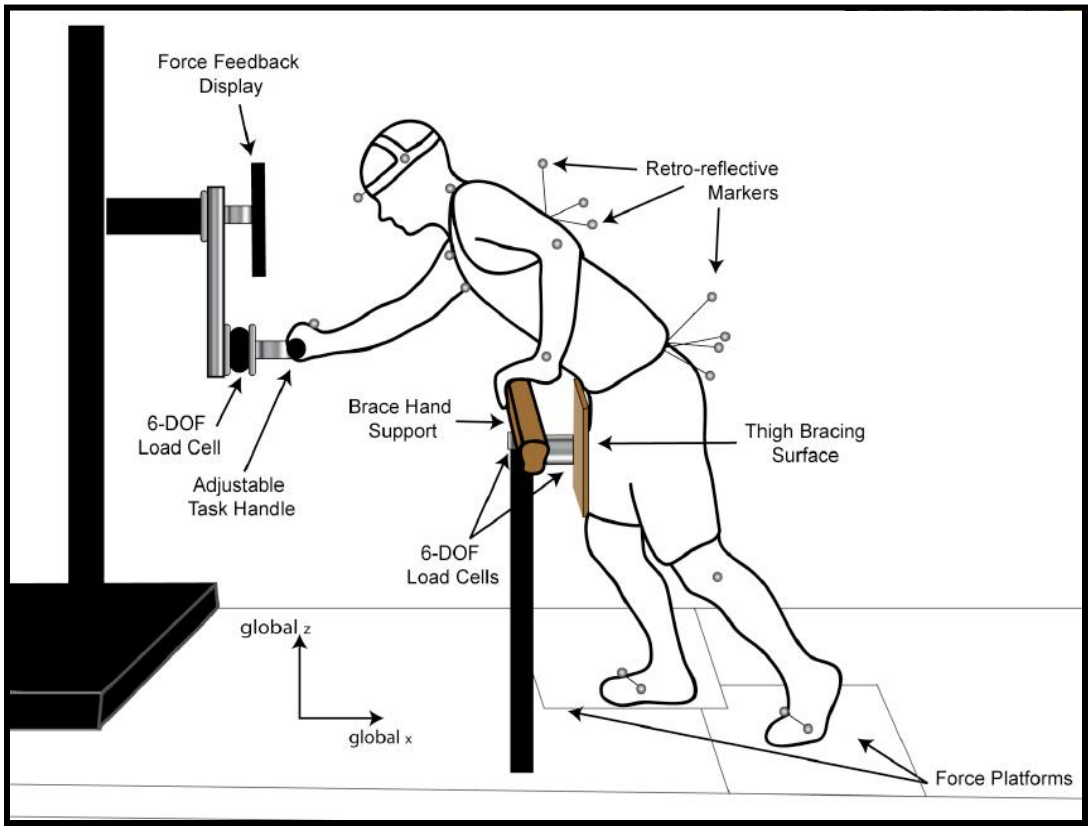


Figure 9: This mockup shows the experimental setup used in Jones (2011). Notably, the horizontal bracing surface is represented by a narrow handrail that ran transversely to the participant.

In summary, each of the three previous leaning/bracing studies reviewed had limitations that my thesis attempted to address. Fewster (2013) and Cappelletto (2013) did not test conditions where participants were completely unconstrained in terms of both external support behaviours and stance. Next, experimental setups in both Fewster (2013) and Jones (2011) did not provide satisfactory hand leaning surfaces that reflected realistic workplace scenarios. Meanwhile, Jones (2011) gave participants the option to lean and/or brace with stance unconstrained, however the measured task hand force directions were not controlled to be within the “nominal” (or intended) direction. This is not reflective of typical manufacturing tasks since successful part installation usually requires an “in-line” force application (e.g. hose, electrical connector, etc.). Finally, all three studies only tested gross motor force exertions at the task hand, and did not test for the effects of fine motor tasks, which are commonplace in automotive manufacturing tasks.

2.4 Predicting Kinematic and Kinetic Characteristics of External Support

There are few studies that have attempted to model and predict the external support forces during one-handed tasks. Chiang et al. (2006) retooled Jack's (Siemens Corporation, Ann Arbor, MI) ForceSolver module by adding an option to incorporate either a leaning hand or an external bracing option. For external bracing (Figure 10), the algorithm is simple; an external bracing body part is selected by the user, then the program assumes that the human is self-supporting at that contact point and, as a result, all joint moment outputs, at or below the point of bracing, are blacked out and ignored. For leaning (Figure 11), when a leaning hand is selected by the user, the algorithm will increasingly iterate the load at the leaning arm shoulder until it reaches its strength limit threshold. Once this is reached, the force magnitude at the leaning hand is fixed, and the same process is repeated at the task shoulder. This leaning algorithm was based on an assumption that a worker will maximize the moments at the shoulders within their strength. However, Hoffman (2008) found that participants postured themselves to maintain the moments at the shoulder below a threshold of ~37 Nm, independent of hand force and task configurations, rather than maximize the demand on the shoulders. Jones (2011) also found participants generally aimed to reduce the moment at the leaning shoulder, within a given force generation strategy (FGS), by either; 1) modifying the force vector of the leaning hand to be in line with the shoulder, or 2) modifying the position of the leaning shoulder to decrease the moment arm at the leaning shoulder. She also noted that task shoulder moments were managed by altering the position of the task shoulder relative to the handle so that moment arms were decreased for a given hand force direction. Furthermore, other studies looking at fine motor tasks, and submaximal gross motor tasks, have quantified the relative force level and found that these values are quite low at between 5%-15% of body weight (Fewster, 2013; Godin et al, 2008; Lardi & Frazer, 2003). Therefore, the Chiang et al. (2006) algorithm for predicting leaning hand forces in DHM programs is inconsistent with findings in the literature.

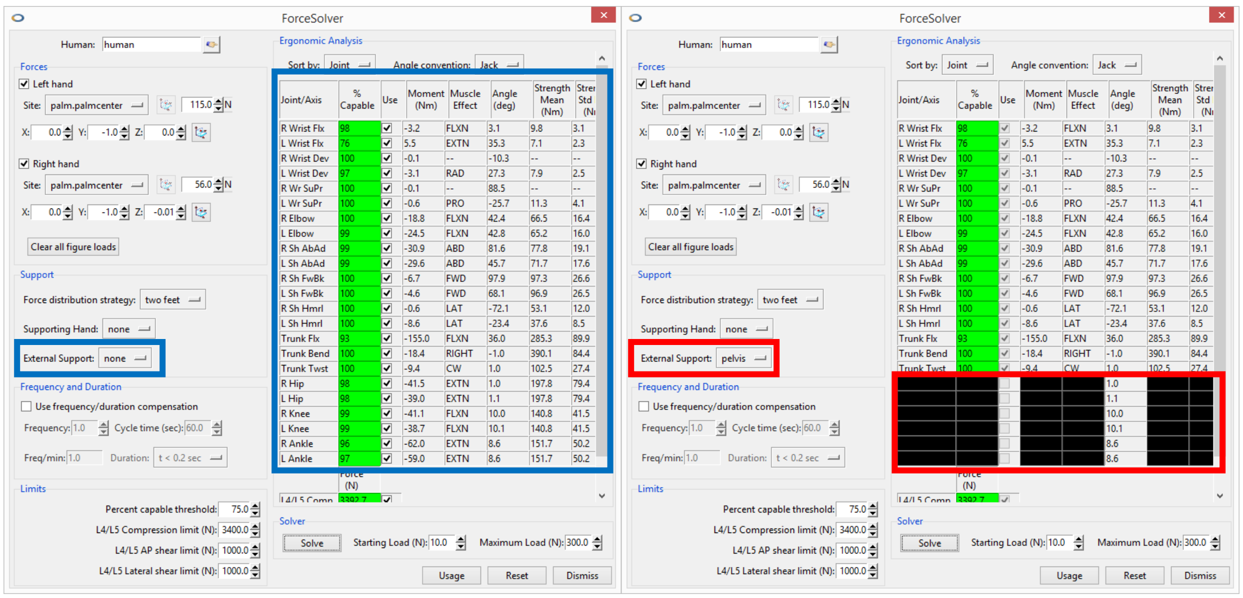


Figure 10: The ForceSolver output module, from Jack Static Strength Prediction (Siemens Corporation, Ann Arbor, MI), shows the resultant outputs for a one-handed force exertion. Outputs without external bracing (left) and with external bracing at the pelvis (right) are shown. Note the blacked out moment outputs for all joints at and below the pelvis in the output that incorporates external bracing.

As an alternative to the method of Chiang et al. (2006), Howard et al. (2012) created an optimization model to predict the leaning hand forces during one-handed automotive assembly tasks. The model used the postures and hand forces from Godin et al. (2008), and was able to predict these hand forces within the 95% confidence interval calculated from the standard deviation from the experimental data. For their model, Howard et al. (2012) started by deriving three aspects of a given posture: 1) the joint torques and resultant reaction load (from a biomechanical linked segment model), 2) the 3-D “zero-moment point” (3D-ZMP), and 3) the stability area (Figure 12). The resultant reaction load is defined as the resultant force vector, of all loads acting upon the body, required to maintain a static posture. The 3D-ZMP is defined as the point in space where the net moment acting on the participant (including those from gravitational forces, external support forces, and task hand forces) equal zero. For example, with no external forces, the 3D-ZMP is equivalent to the participant's center of mass. The resultant reaction load vector was assumed to act from this point. The "stability area" is the region on the ground that is defined by axes created between pre-determined contact points at the ground (e.g. the heels, hallux, etc.). Through a series of calculations, the authors determined the moments caused by the resultant reaction load at the 3D-ZMP about each stability axis (i.e. the lines connecting the contact points). A posture is assumed to be stable if all these moments are positive. Conceptually, if the resultant reaction load vector from the 3D-ZMP acts through the stability area, the posture will be considered stable, as no destabilizing moments would be created. Contrarily, if the resultant reaction load vector acts outside of the ground contact area, a destabilizing moment would be generated (Figure 12 & Figure 13).

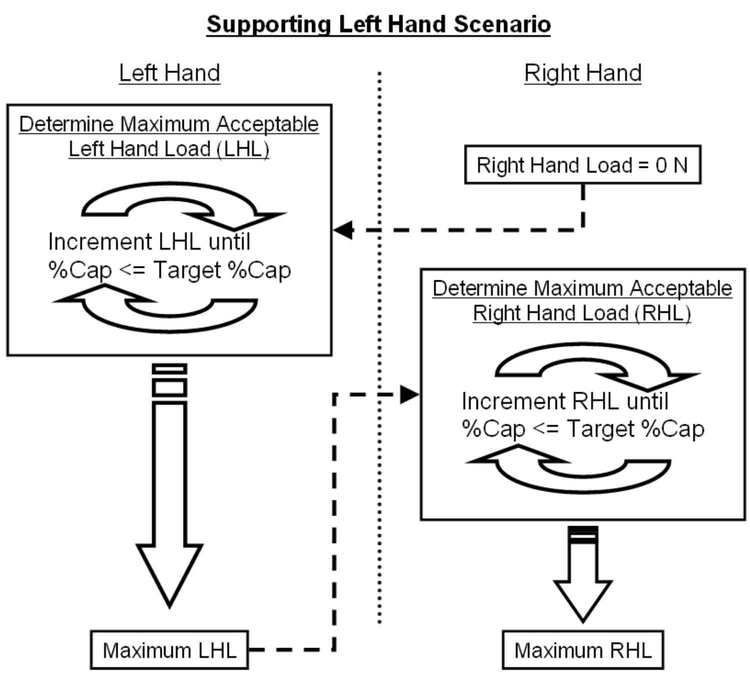


Figure 11: The algorithm used by Jack (Siemens Corporation, Ann Arbor, MI) for the determination of leaning hand forces. This example shows the selection of the left hand for leaning, for which the right hand force is first set to zero, then the left hand force is iterated up until it reaches strength capability threshold. Once this force is found, it becomes fixed, and then the right hand goes through the same iteration process (Chiang et al., 2006).

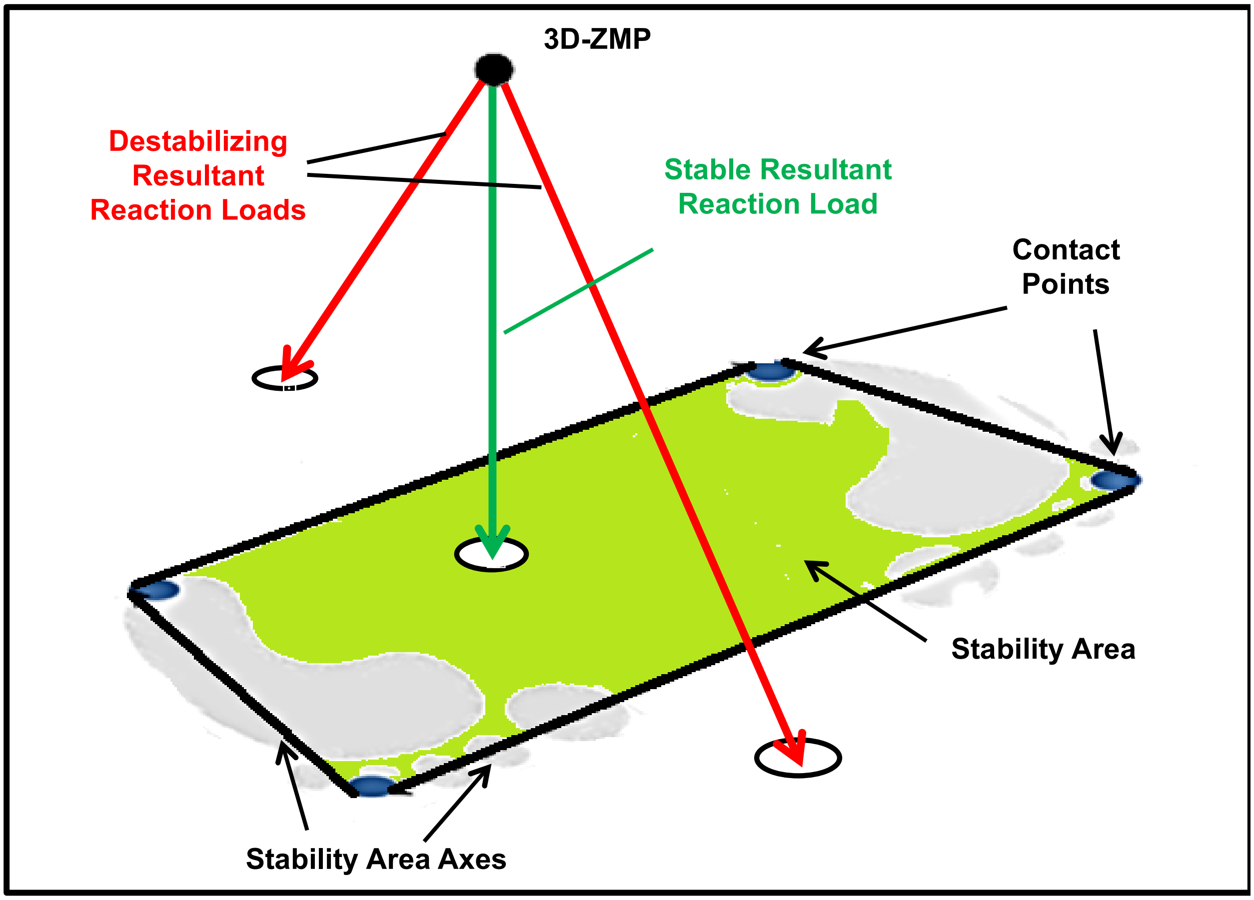


Figure 12: This diagram illustrates the stability model, adapted from Howard et al. (2013). The 3D-ZMP is the point at which all moments (internal and external) about the body equal zero. From the 3D-ZMP, a resultant reaction load (defined as the resultant force vector required to keep maintain a static posture) will act. If the direction of this vector acts through the stability area (green), the posture is said to be stable. If it acts outside the stability area, a destabilizing moment will be created that will cause the participant to lose balance.

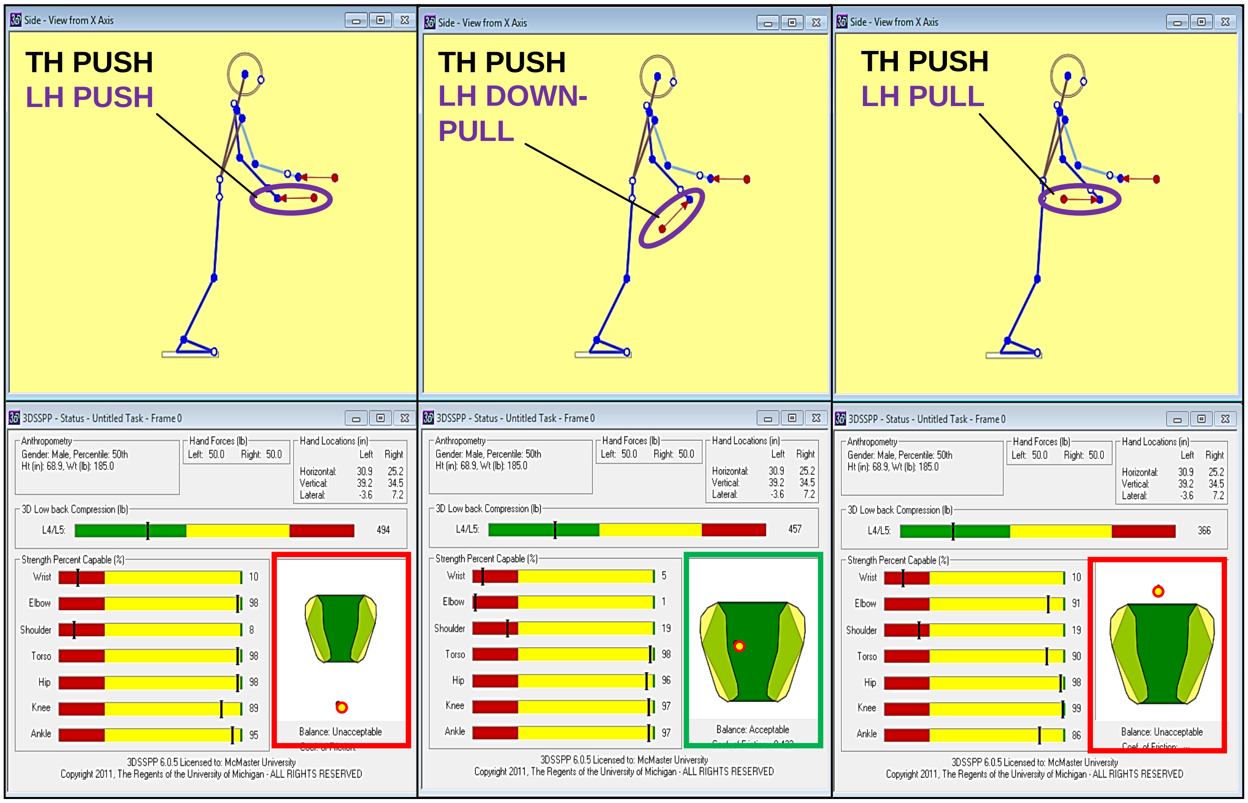


Figure 13: Three 3DSSPP outputs demonstrate how changes in leaning hand (LH) force direction changes the stability of a posture, during task hand (TH) pushes. The top view of each window shows the linked segment model and the corresponding hand force directions (red arrows). In the lower views of each window, a green (stable) or red (unstable) box highlights the stability analysis. The stability area (green pentagon) and the intersect point of the resultant reaction force vector with the ground are shown (red circle). If the intersect point is outside the stability area, the software deems the balance of the posture as unacceptable, and vice versa.

An optimization method was used to solve the indeterminacy of input parameters by determining the lowest possible leaning hand force with which; a) the resultant reaction load vector acted within the stability area, and b) the joint torques did not exceed the strength limits of each respective joint. While the model was able to accurately predict actual outcomes from experimental data, the model only accounted for postures that have one task hand and a leaning hand for support, and has not been validated for tasks that incorporate body bracing.

Jones (2011) attempted to predict characteristics (direction and magnitude) of task hand force capability, leaning hand force and thigh bracing force. She used a regression analysis for backward, upward, and forward task hand force directions, with inputs such as task hand location, support surface availability, task hand force direction, force generation strategy, and participant strength and anthropometry. While many r^2 values were reported, Jones suggested that "moderate to strong predictions" were observed for all model outcomes: task hand force magnitude ($r^2 = 0.17$ to 0.65), leaning hand force magnitude ($r^2 = 0.13$ to 0.71), leaning hand force direction ($r^2 = 0.18$ to 0.51), and thigh bracing force magnitude ($r^2 = 0.40$ to 0.94). Horizontal and vertical task handle location were significant predictors of all three characteristics (task, leaning hand, and bracing force) and FGS. Of interest, leg strength and stature were both significant predictors for task hand force capability. For the external support forces, task hand force level was the most influential predictor of both external support forces at the hand and thigh, as the higher task hand force increased the external support force generation. Furthermore, the task handle height was a strong predictor of leaning hand force, while the task handle horizontal reach was a strong predictor of thigh bracing force.

Finally, Jones (2011) created a model to predict the various postural trends of the participants, including the fore-aft (horizontal) location of the pelvis, the vertical position of the pelvis, the torso inclination angle, and the task and leaning shoulder heights. Each of these parameters was predicted for each FGS within each of the three task hand force directions. Moderate to strong r^2 values were reported for all predictions.

2.5 Predicting the Occurrence of External Support Behaviours

While kinematic and kinetic outcomes are important to predict, it is also very important to predict the occurrence of external behaviours for the sake of proactive ergonomic assessments. Jones (2011) modelled these behaviours by creating a series of predictive models, each addressing a different prediction output. These included the prediction of: 1) choice of force-generation strategy, 2) task hand force magnitude, 3) external support force magnitude and direction, and 4) changes in postural variables. All of these predictive models were based on task parameters and participant input parameters. To start, the author classified her experimental samples into five different FGSs: 1) no bracing (NB), 2) hand bracing (HB), 3) thigh bracing (TB), 4) hand & thigh bracing-aligned (HTB-a) where the force direction of the thigh bracing was in the same direction as the task hand force, and 5) hand & thigh bracing-opposed (HTB-o) where the thigh bracing forces are in the opposite direction to that acting on the task hand. For example, Figure 14 shows the choices of FGS when both the leaning and bracing surfaces were available for backward, forward, and upward task hand force directions.

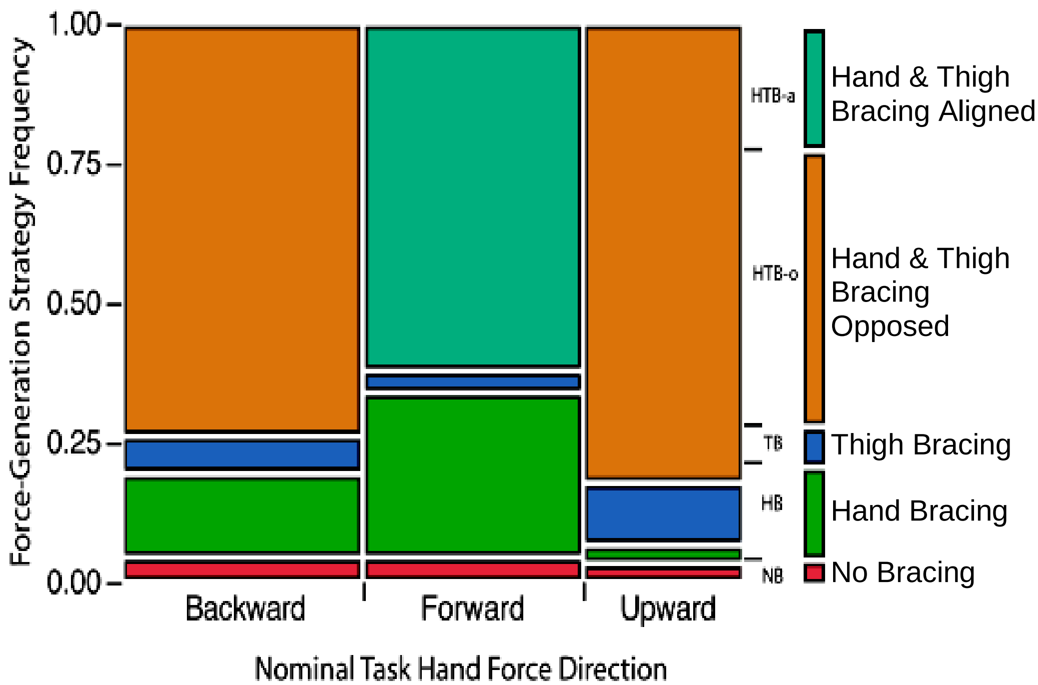


Figure 14: This mosaic plot (adapted from Jones, 2011) shows the distribution of force generation strategies (FGS) for various nominal task hand force directions, combined across all task hand force directions and locations. The nominal task hand force direction defined as the intended force direction. The thin plot graph on the right shows the cumulative frequency of each FGS across all task hand force directions.

Postural variables, within each classification of FGS, were said to be more “internally homogeneous” than the entire data set (i.e. postural variables are similar within a FGS and dissimilar between different FGSs). Thus, data clustered into individual, discrete FGSs were said to “increases the accuracy of predictive models” (Jones, 2011). Using a logistic regression analysis, Jones (2011) assessed the association of task configuration and participant characteristics as predictors of FGS for backward, forward, and upward task hand exertions. Inputs included task hand location (vertical and horizontal), task hand force level, external support surface availability, stature, body mass index (BMI), and various strength measures. The models correctly predicted FGS for 83% of backward (Figure 15) and upward exertions, and 65% of the forward exertions. The most significant predictors were the task configuration parameters (task handle location) for all force directions.

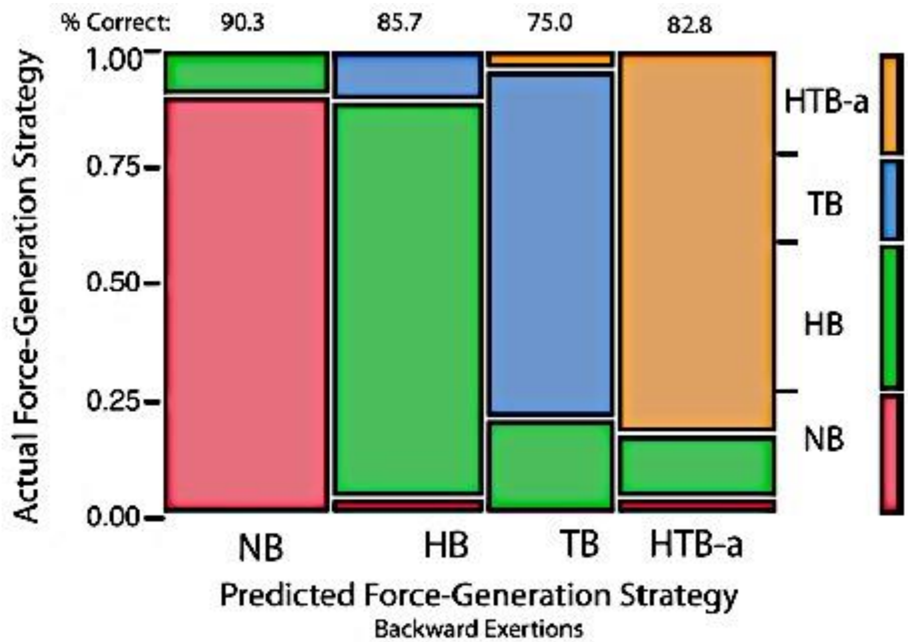


Figure 15: This mosaic plot from Jones (2011) shows the prediction of FGS (x-axis) compared to actual FGS seen from the experimental trials (y-axis) for backward task hand force exertions. A perfect prediction model would have a single colour in each FGS column. For this example, the model correctly predicted FGS 83% of the time. The thin plot on the right shows the cumulative frequency of all FGSs that were predicted for backward task hand exertions.

Cappelletto (2013) and Fewster (2013) followed up the FGS prediction modelling of Jones (2011), by performing logistical regression analyses to predict bracing or leaning behaviours, respectively, for constrained environments with one-handed submaximal gross motor force exertions. Input parameters for both studies included; task configuration parameters (task hand reach and height), task demands (force level and force direction), individual participant strength parameters, and anthropometric measures. Fewster (2013) reported that her model successfully predicted leaning behaviours 92.2% of the time, and that her model inputs were able to explain 70.3% of the variance in leaning choices. The significant predictors of leaning were elbow and trunk strengths, horizontal task hand location, and horizontal task hand exertion direction. Cappelletto (2013) reported that her model could predict bracing behaviours 79.8% of the time, and that her model inputs were able to explain 34.7% of the variance in the data. The significant predictors were elbow, trunk and shoulder strengths, horizontal task hand location, and vertical task hand exertion direction. The results from the predictive models reported in the three aforementioned studies (Jones, 2011; Cappelletto, 2013; Fewster, 2013) are summarized in Table 2.

While these previous studies have been able to successfully predict different outcome parameters of external support behaviours, my thesis will add a fine motor task to the predictive models. While past studies (Godin et al. 2008; Lardi & Frazer, 2003) have used assembly like precision tasks in their experiments (e.g. bolt fastening, hose insertions, etc.), neither included gross motor tasks to compare the kinematic and kinetic outcomes between the two task types.

2.6 External Support and Fine Motor High Precision Tasks

Few studies have been performed that have specifically analyzed external support behaviours and their relationship to fine motor, or high precision, hand tasks. However, there is both theoretical and empirical evidence that strongly suggests that precision of tasks could influence the occurrence of external support, and concurrently, that the occurrence of external support can enhance the performance and comfort of the participant performing the task.

Table 2: The below table summarizes the results of the predictive models of external support behaviour reported in the three most relevant studies outlined in this thesis. “Behaviour” indicates the support strategy being predicted, while “% Correct” indicates the percentage of times the model correctly predicted the behaviour. R^2 values and significant task and participant input variables are also presented. TH: task hand.

	Cappelletto (2013)	**Fewster (2013)**	**Jones (2011)**
Behaviour	Bracing	Leaning	Force generation strategy (x5)
% Correct	80%	92%	65-88%
R^2	0.35	0.70	N/A
Significant Task Variables	- TH force direction - TH vertical location - TH horizontal location	- TH force direction - TH horizontal location	- TH force direction - TH horizontal location - TH force magnitude - Surface availability
Significant Personal Variables	- various joint strengths	- various joint strengths	- Stature - BMI

From a cognitive perspective, the case for external support, during precision tasks, could be based on the Degrees of Freedom problem (Bernstein, 1967), which states that, for any given movement, the central nervous system is responsible for a nearly-infinite number of independent states. The human body contains many joints that can adopt an almost-infinite combination of joint angles within their allotted degrees of freedom. Some joints have most of their rotations about only one degree of freedom (e.g. knee), while others have three degrees of freedom (e.g. shoulder). Compounding the large number of independent states, that the joints can assume, is the multitude of muscles that control these joints. The central nervous system manages this dilemma by reducing the number of states, that the body can adopt, to make motor control cognitively feasible. I propose that use of external support can freeze the degrees of freedom, for part of the system not required for performing the Precision task (i.e. the lower body), resulting in decreased demands on the central nervous system and improved control of the task limb (i.e. the task arm and hand).

Stability may be another, and perhaps the more likely, reason that one would employ external support while performing fine motor precision tasks. Previous studies show that, when performing tasks with high degrees of precision, there is a significant increase in postural muscle activation (Joseph et al., 2014; Milerad & Ericson, 1994; Visser et al., 2004), thus increasing the stability of the bodily system to improve the accuracy at the hand. Finally, as Gardner et al. (2001) suggested, increasing visual acuity may be another reason for adapting postures for finer, higher precision hand tasks.

Some studies support the theory that external support may aid in the comfort/performance of a participant while performing a high precision task. First, Gardner et al. (2001) compared two fine motor tasks (with either high and low precision demand) in a reaching environment, where horizontal reaches to the target object were incrementally increased. Researchers found that, for the high precision task, the participants were more likely to adopt more comfortable and stable postures at shorter reach distances compared to the low precision task. External support was also observed by the researchers for the longer reaches, causing the authors to state that "Often, [participants] reduced the increased moment around the hips… by supporting the weight of their upper torsos with their left arms" (Gardner et al., 2001). They go on to state that the visual and fine motor demands of the high precision task made it less comfortable for the participants to perform the task without adapting their postural strategy. Second, when observing very high precision work such as surgery or dental work, armrest supports have been tested as an intervention for operator discomfort. Results from these intervention studies show a decrease in muscle activity, discomfort rates, and task errors as a result of these armrests (Galleano et al., 2006; Milerad & Ericson, 1994). Finally, Albayrak et al. (2001) tested a novel chest support apparatus for surgeons and found a significant decrease in postural muscle activity. In addition, six of the seven surgeons provided verbal feedback stating that the support was comfortable and would be used again in the future. The external supports provided in the three aforementioned studies could have improved comfort, increased the participant's stability, and/or reduced the degrees of freedom to reduce cognitive load while performing high precision tasks.

In summary, I suggest that external support may be voluntarily employed during precision tasks due to one, or a combination, of the following effects: 1) increasing the postural stability of the bodily system by anchoring it to a solid object, 2) decreasing the cognitive load on the central nervous system by restricting the degrees of freedom of the bodily system's movement, and/or 3) improving the visual perspective about the target. These all may also contribute to the accuracy of the performance of the task.

3.0 METHODS

3.1 Participants

Conventionally, proactive ergonomic virtual work simulations are assessed using a 50th percentile digital human manikin as their standard model. A job is deemed acceptable if the strength demands on the manikin are acceptable for 75% of the female population (Chaffin, 2005). Jones (2011) showed that the effects of anthropometric and strength variables, on various experimental outcomes, are independent of gender. Therefore, only females (n = 18) were asked to participate in my study. Eligible participants were right-handed and free from upper body injury or musculoskeletal disorders. Furthermore, only participants who were 18-55 years of age were used to best represent the working population. They were asked to arrive wearing form-fitted, non-reflective clothing, preferably shorts and tank-tops, and non-reflective active-wear shoes.

Participants were asked to read a letter of information and sign a consent form before participating in the study. These documents provided the participant with everything they needed to know about the study, including experimental protocol and any potential risk that may be associated with the experiment. The experimental protocol was approved by the McMaster University Research Ethics Board.

3.2 Data Collection and Instrumentation

3.2.1 Experimental Setup

3.2.1.1 Kinetic Data Acquisition

Two tri-axial load cells (large force plates), with 6 degrees of freedom (3 bipolar force and 3 bipolar moment measures), were used to measure kinetic data associated with the leaning and bracing behaviours of the participants during the trials. For the “bracing surface”, a force plate (OR6-7-1000, Advanced Mechanical Technology, Inc., Newton, MA) was positioned vertically and facing the participant, with the top edge of the plate at each participant’s knuckle height, or roughly mid-to-upper thigh height; this has been seen to be a major point of contact for bracing in automotive assembly (Cappelletto et al., 2012). The plate was attached to a rigid apparatus of slotted aluminum rails (80/20 Inc., Columbia City, IN) which was vertically adjustable to account for differences in stature between the participants. An apparatus was constructed for the leaning surfaces. A large steel plate (76 cm L x 47 cm W x 3 cm D) was bolted on to a force plate (OR6-5-1, Advanced Mechanical Technology, Inc., Newton, MA), which formed the “horizontal leaning surface”. The purpose of the steel plate was to increase the leaning surface area available to the participant. Second, a 100 cm long (8 cm W x 8 cm D) rigid aluminum post was mounted vertically to the steel plate at the corner that is closest and to the left of the participant. This formed the “vertical leaning surface”. The post was long enough to provide an available leaning surface between the knuckle and eye level, which Cappelletto et al. (2012) observed to be the most common range for vertical position of the leaning hand in automotive assembly (it simulated an A- or B-pillar of a vehicle). The force plate measured 3 forces and 3 moments at both the horizontal and vertical leaning surfaces. The vertical leaning surface was made to be very rigid, and pilot testing was performed to ensure that forces applied to this surface measured by the force plate were accurate. The leaning apparatus (consisting of the force plate, steel plate, and post) was then secured to a simple hydraulic lift (MotoMaster 1500 lb Motorcycle Jack, 09-1015-2, Canadian Tire Corporation, Toronto, Canada), which allowed for vertical height adjustment. The height was set so that the horizontal leaning surface was at knuckle height of the participant, and flush with the top edge of the bracing surface (Figure 19).

A custom-made, rigid steel apparatus (Figure 18), adjustable within three degrees of freedom (vertical, lateral, and anterior/posterior planes) to control the task locations, was used to as the attachment point for the task elements. Two types of task elements were mounted to the apparatus and used to perform the different task types (gross and fine motor tasks). A tri-axial load cell (M 4176, Advanced Mechanical Technology Inc., Watertown, MA), with an attached vertically oriented cylindrical handle (Figure 16), acted as the task element for the gross motor task condition. The load cell measured forces associated with the task force exertion. For the fine motor task condition, a custom built nut-and-stud task was used as the task hand element (Figure 17), which represented hand-starting a nut onto a bolt, as commonly seen in automotive assembly. The device for this task was built into a small, removable package that was easily mounted and dismounted from the force handle device. It involved 3 main parts: 1) the main bracket, which was clamped to the task handle on one side, while presenting the bolts to the participant on the other side, 2) two identical bolts, which were seated in the main bracket, and 3) one nut, which was compatible with both bolts seated in the main bracket.

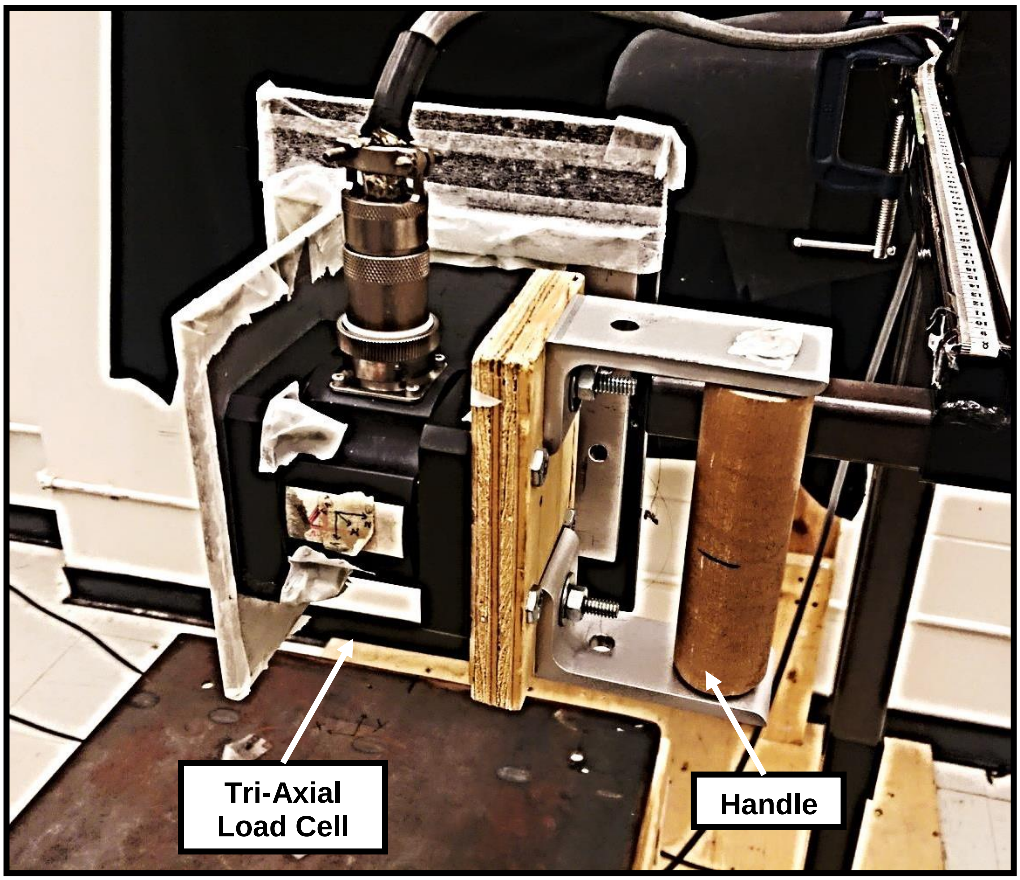


Figure 16: Image of the task hand element that was used for the gross motor task (maximal force exertions).

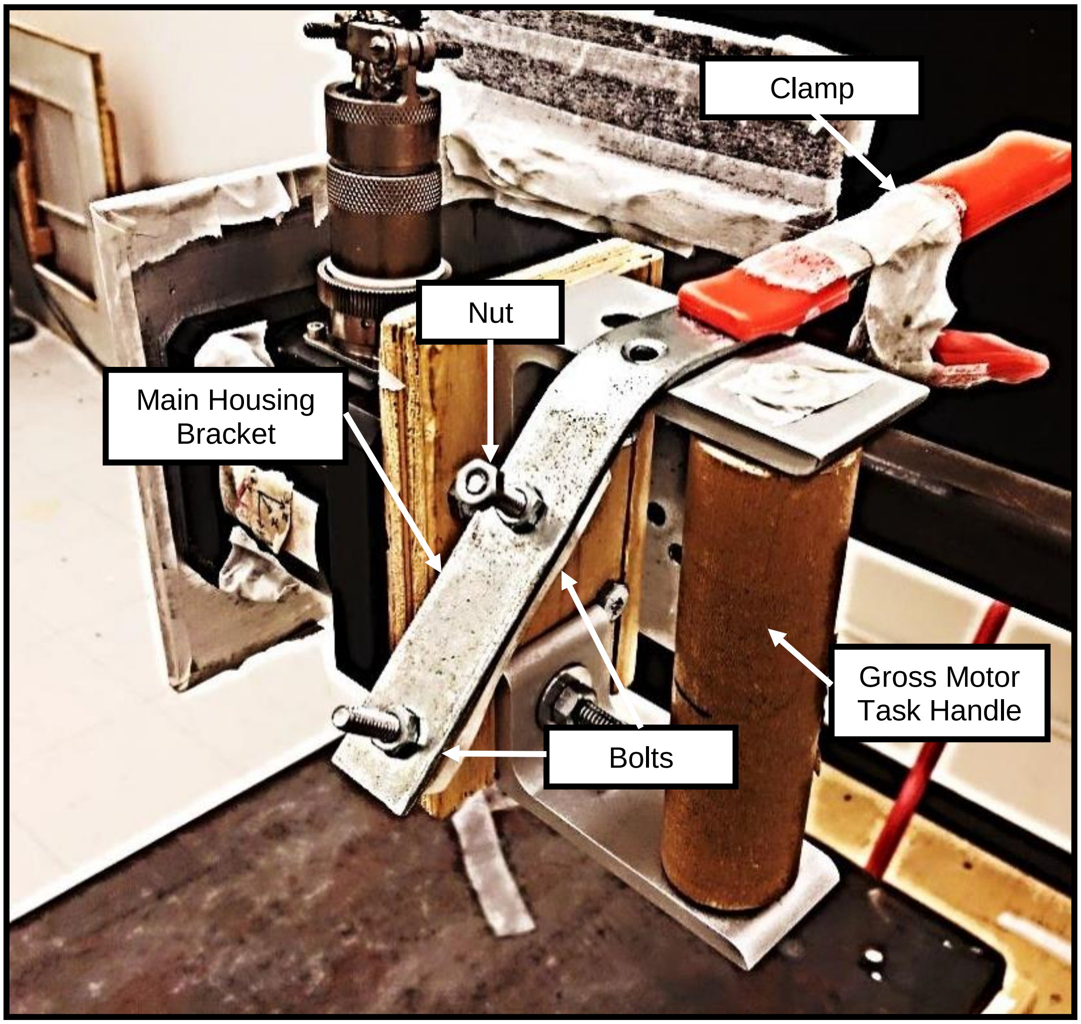


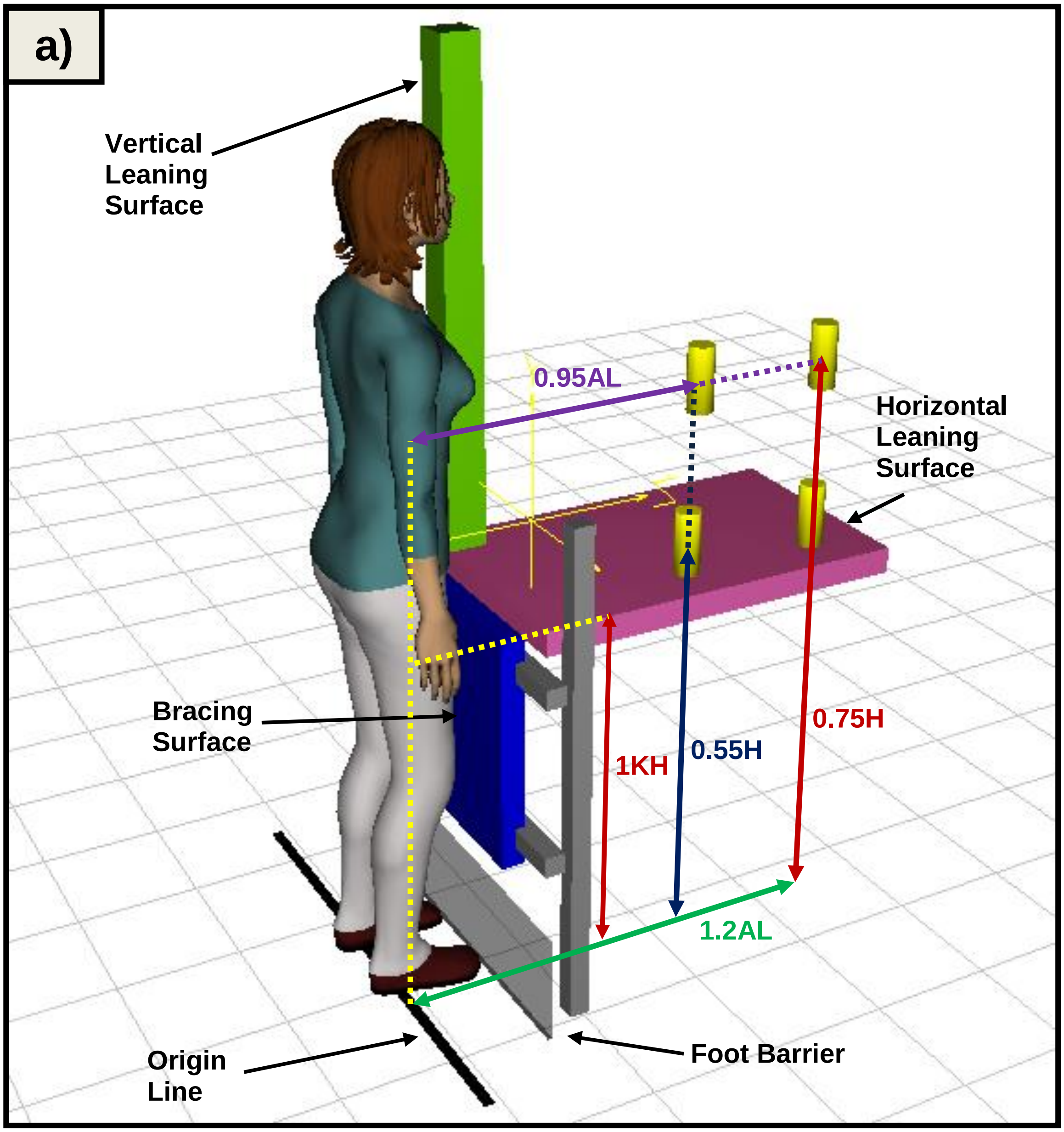
Figure 17: This image shows the custom made Precision task element, which was mounted on to the gross motor task hand element using a clamp. Note the two target bolts, which the nut gets secured to during the Precision trials.

Figure 18: This image shows the custom-made steel apparatus that was used to mount the task hand elements (not shown with the rest of the apparatus here). It could be adjusted within three degrees of freedom (vertically, laterally, horizontally) to satisfy the range of demands for all task hand conditions.

All force data were collected at 100 Hz using custom LabVIEW software (National Instruments, Austin, TX), and were converted using a 16-bit A/D converter (NI USB-6229, National Instruments, Austin, TX). The sampling frequency was chosen so that it could be easily synced with kinematic data (see 3.2.1.2).

A long, dark piece of electrical tape was placed on the floor in front of the bracing surface underneath where the participant would stand, running laterally and medially (along the z-axis), and will hereby be called the “the origin line”. The horizontal position of the origin line, relative to the bracing surface, was equivalent to the length of the participant’s foot excluding the heel (defined as the mid-point of the ankle to the tip of the shoe). Unlike previous studies (Cappelletto, 2013; Fewster, 2013), where the line was used as a constraint to control participants’ double stance, this experiment only used the origin line as the reference point when determining horizontal distances to the task element. While the origin line was used as the starting standing point for each trial, participants were able to change their stance independent of the origin line. However, a wooden barrier was secured to the ground, in-line with the front edge of the bracing surface, which constrained forward positioning of the feet.

A simplified schematic of the setup can be seen in Figure 19, while photographs can be found in Figure 20.


a)
Vertical Leaning Surface
0.95AL
Horizontal Leaning Surface
Bracing Surface
1KH
0.55H
0.75H
1.2AL
Origin Line
Foot Barrier

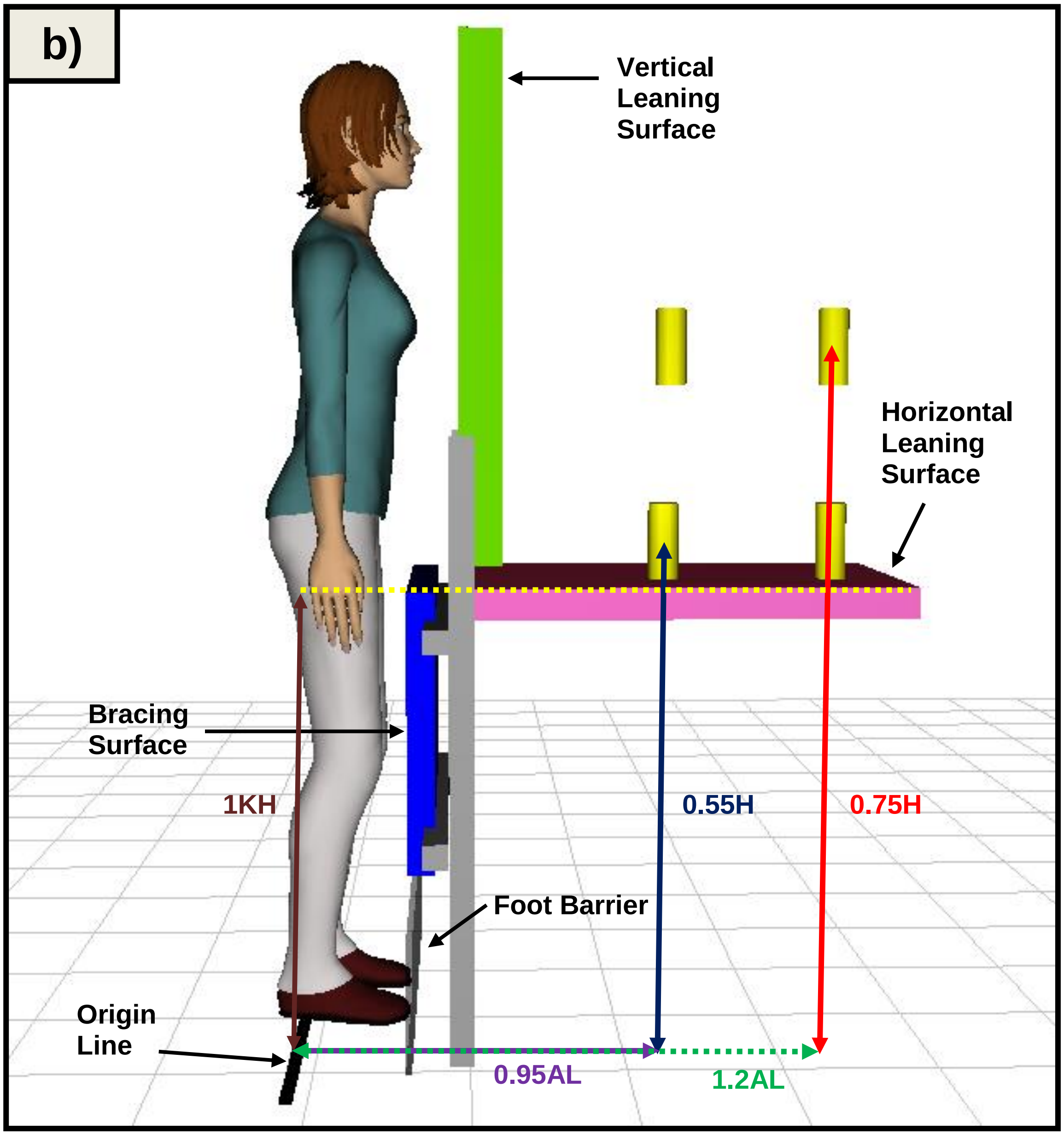


Figure 19: This 3D figure illustrates a simplified schematic of the experimental setup, from a) an oblique view, and b) a sagittal view. The yellow cylinders represent the four task hand Locations (Low-Close, Low-Far, High-Close, High-Far), while the dimensions of these locations are indicated with the arrows, with “H” and “AL” representing to the participant’s stature and arm length, respectively. The three external support surfaces (bracing, horizontal leaning, and vertical leaning) are also shown. The height of the both top edge of the bracing surface and horizontal leaning surface are equivalent to the knuckle height of the participant (1KH).

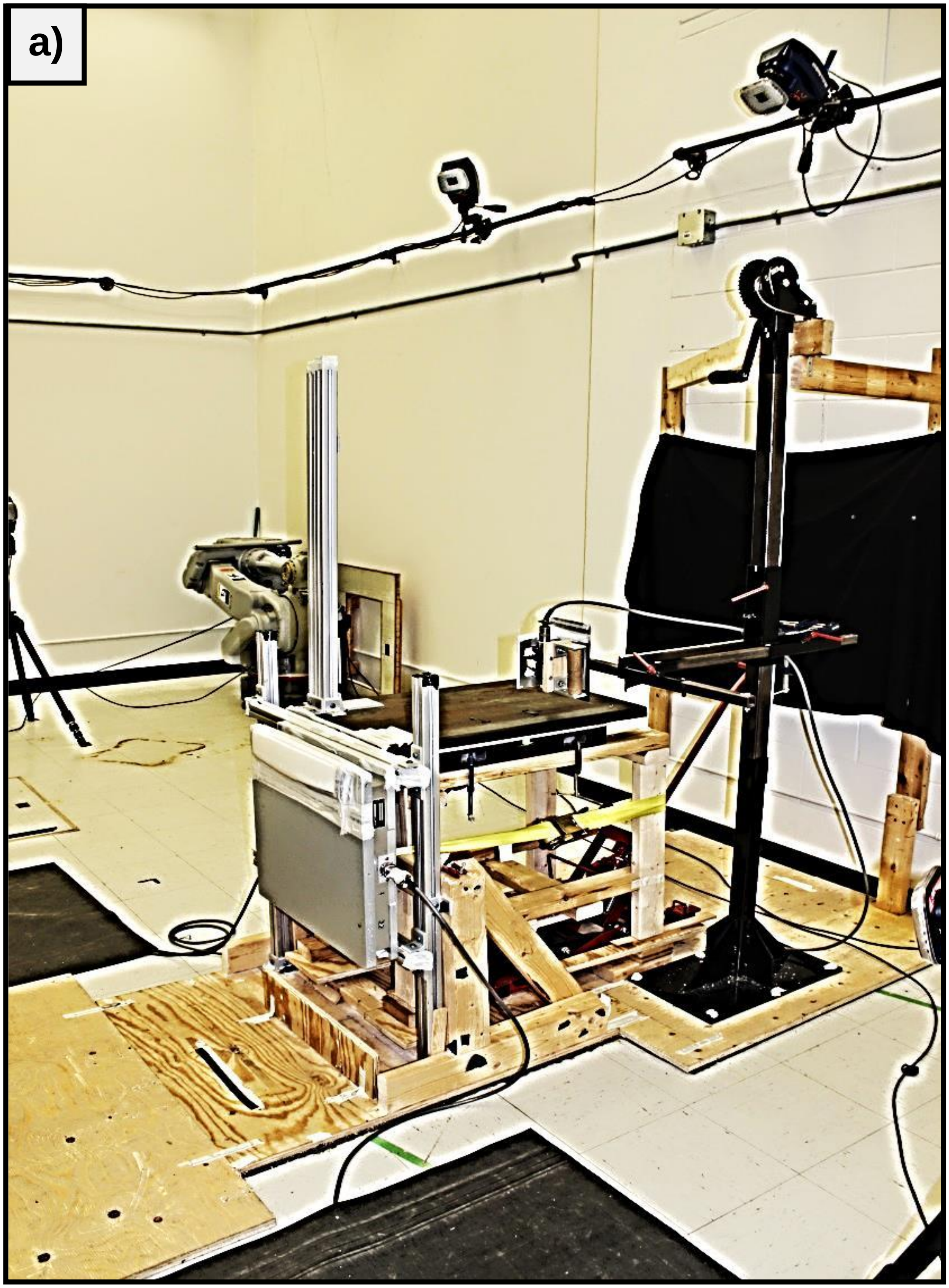

a)

Figure 20: This figure provides photographs of a) the apparatus, and b) the apparatus while in use by a participant.

3.2.1.2 Kinematic Data Acquisition

A passive system was used to perform motion capture for this study. Twelve Raptor-4 digital infrared cameras (Raptor-4, Motion Analysis Corporation, Santa Rosa, CA) were mounted around the participant and experimental apparatuses to collect kinematic data during the trials. Fifty-two reflective markers were placed on each participant using an adhesive backing. The landmarks for marker placement followed the guidelines as defined by Potvin et al. (2008) to define 27 skeletal segments (Figure 21 a), b), & c)); exact guidelines can be found in Appendix B. The data were collected at 100 Hz using Cortex 4.1.1 motion capture software (Motion Analysis Corporation, Santa Rosa, CA), which formed a multi-segmented human model using the markers (Figure 21 d)).

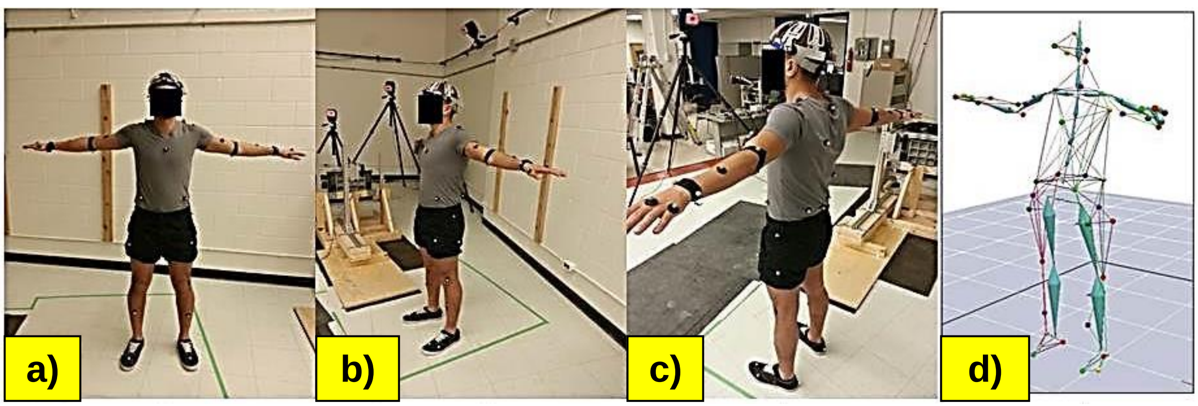


Figure 21: Sample photographs of a participant wearing the 52 reflective markers in accordance with Potvin et al. (2008), including: a) front view, b) oblique front view, and c) oblique rear view. Finally, d) shows the multi-segmented model created by Cortex 4.1.1 motion capture software that was used to represent and quantify the kinematics of the participant. Details on all exact 52 marker locations are found in Appendix B.

3.2.2 Standardized Strength Testing

A Biodex 4 isokinetic dynamometer (Biodex Medical Systems, New York, NY) was used to perform the standardized isometric strength testing (see details below). The Biodex user's manual was consulted to ensure proper setup and protocols are employed for each of the strength tests on varying joints and joint motion types. The strength data were sampled at 100 Hz.

Maximal handgrip force was also measured using a digital handgrip dynamometer (MIE Medical Research Ltd., Leeds, United Kingdom). Similar to the shoulder, elbow, and trunk testing, participants performed two trials (separated with sufficient time to recover), and the higher force was used to determine the handgrip strength of the participant.

3.3 Experimental Protocol

3.3.1 Introduction, Strength and Anthropometric Testing

First, participants were introduced to the laboratory, including the experimental setup and the motion capture instrumentation, and were given a general description and demonstration of the experimental protocol. Once participants read the letter of information and signed the consent form (Appendix A), basic anthropometric data collection began. First, the participant's mass (kg) was measured using a standard weigh scale. Next, anthropometric measurements were recorded using a standard metric tape measure. The participant was instructed to stand in the anatomical position while I performed three measurements: 1) participant's stature (H), defined as the distance between the top of the participants head to the ground, 2) arm length (AL), defined as the distance between the middle of the lateral border of the acromion of the scapula to the tip of the distal phalanx of the 3rd digit, and 3) knuckle height (KH), defined as the distance between the 3rd metacarpophalangeal joint and the ground. Stature was used to define the height of the leaning/bracing apparatus and the task element locations, while arm length was used to define the horizontal distance of task element locations relative to the baseline.

Next, strength testing was conducted using the Biodex dynamometer to determine the strength capabilities of the participant's trunk, right shoulder, and right elbow. A total of 8 conditions in total were performed, which included: trunk flexion and extension, shoulder flexion, extension, abduction and adduction, and elbow flexion and extension (Figure 22). Each condition tested isometric strength and were performed twice, with a minimum two-minute rest period in between each trial to allow for recovery from any fatigue caused by the efforts. The peak moment (Nm) outputs were recorded from each trial and the higher of the two was taken as the participant's maximum strength.

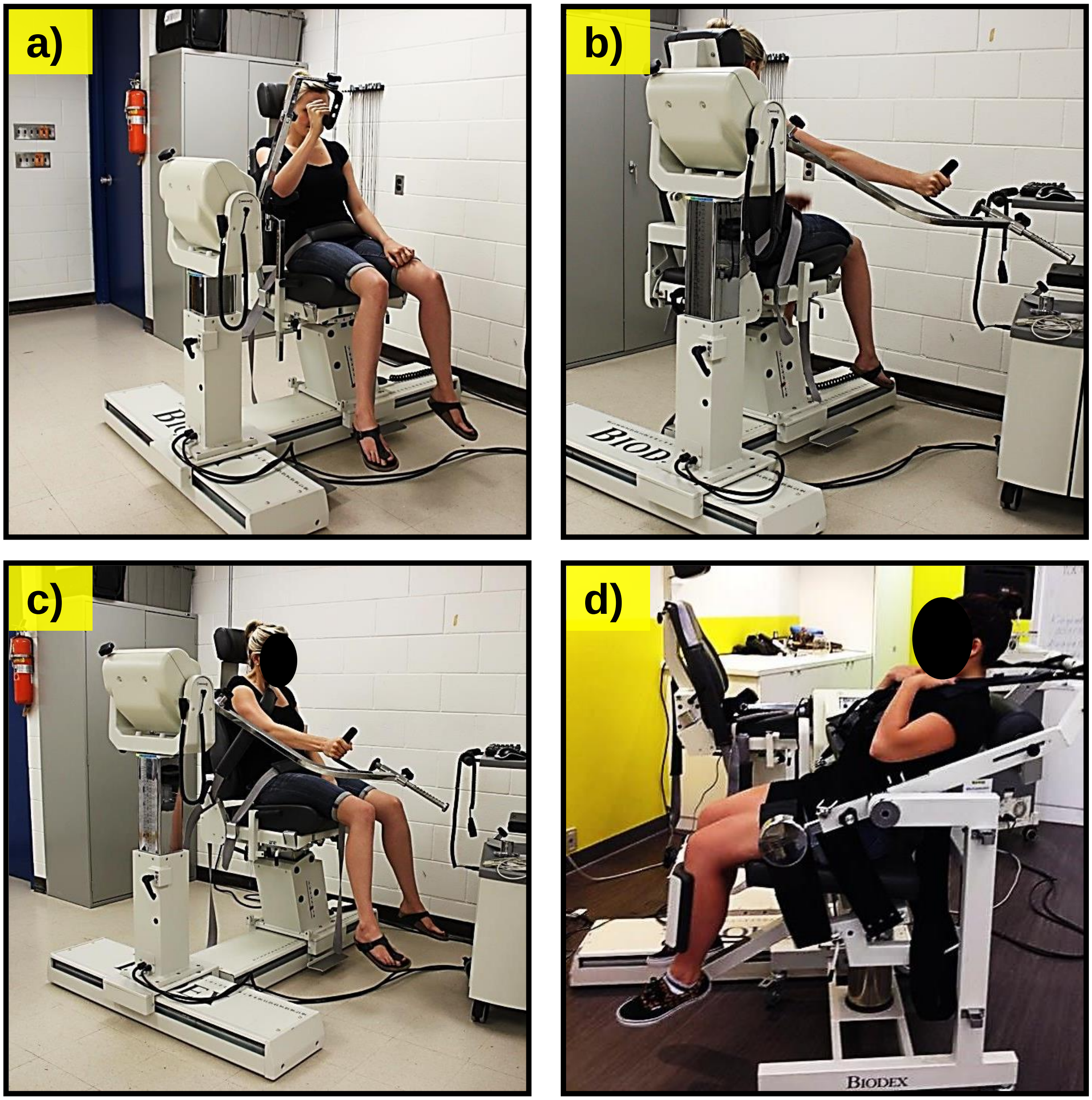


Figure 22: Sample photographs of participants performing the isometric strength testing protocols using the Biodex 4 isokinetic dynamometer: a) Testing of elbow flexion/extension strength, b) testing of shoulder abduction/adduction strength, c) testing of shoulder flexion/extension strength, and d) testing of trunk flexion/extension strength.

3.3.2 Kinematics Setup and Practice Protocol

First, the capture space was calibrated before the participant is outfitted with the reflective markers. This was performed using an L-frame origin and a T-shaped wand with an asymmetrical reflective marker distribution. The participant was then outfitted with the 52 reflective markers. The body landmark placements were those as described in Appendix B. After the participant was outfitted with markers, they then stood in a T-position (Figure 21), followed by a series of maximum range movements (including standing trunk flexion/extension, lateral lunges, arm rotations, and a mock experimental trial) so that the multi-segmented skeletal model could be built in Cortex.

The leaning and bracing apparatuses were set to the appropriate heights (1KH) before participant arrival. The participant was then asked to perform a series practice trials, which involved two of the task hand Location conditions (Low-Far and High-Close), while each task type was trialed at least once within these task hand locations. These practice trials allowed the participant to get accustomed with the apparatuses, and different experimental conditions, protocols and constraints. It also allowed the participant to become familiar with different postural strategies they may employ during the experimental trials. Of particular interest was the precision task, where the participant was asked to perform a minimum of 10 practice trials to control for learning effects during the experiment.

3.3.3 Experimental Trials

Each trial started with the participant standing in the T-pose with her ankles over the origin line, facing the task hand element and leaning/bracing apparatuses. Once the motion capture system recognized the marker skeleton, the participant was instructed to perform the task. The participant was given a 12 seconds window to complete the trial. The participant’s stance was not constrained, as she was free to re-position her feet once the trial has started. There was also a minimum of two minutes of rest period between each trial to minimize the effects of fatigue.

Each condition varied based on a set of the following variables: 1) task hand Location (n = 4), 2) task hand exertion (total, n = 7; maximal effort gross motor tasks, n = 6; fine motor Precision task, n =1), and 4) Support choice (n = 2) (Table 3). The task hand Locations consisted of a combination of different vertical heights and horizontal reaches. The two vertical heights were “Low” and “High” (55% and 75% of the participant’s stature, respectively); while the two horizontal reaches were “Close” and “Far” (95% and 120% of the participant’s arm length, respectively). Therefore, a total of four task hand Locations were tested (Low-Close, Low-Far, High-Close, High-Far). Within each hand Location, the task hand exertions were performed.

The gross motor tasks were maximal force efforts performed in six different orthogonal force Directions: Superior, Inferior, Anterior, Posterior, Medial, and Lateral. Participants were instructed to ramp up from zero force to maximal force within approximately two seconds, followed by a very brief hold of the maximal force, and then ramp down quickly to relaxation. A maximal effort was deemed successful if the force in the required direction was at least 90% of the resultant force.

The fine motor Precision task was performed once at each task hand Location, which involved hand-starting a nut onto a small bolt. The procedure would start with the nut already seated to one of the bolts (Figure 17), and when instructed to begin, the participant would unscrew the nut from its current bolt, and then secure it on to the other bolt. The participants were told to perform the task as quickly as possible. In the case of an error (e.g. dropped nut), the procedure would be performed again until a successful trial was performed.

For all tasks, I determined external support to have occurred if the measured resultant force from the leaning and/or bracing plates exceeded a predetermined force criteria of 10 N. The 10 N value was qualitatively estimated to be enough force to influence the balance/strength of the participant. It was used to rule out trials where “light touch” may have been used by the participant (for reasons such as proprioception).

Table 3: This table shows the different combinations of conditions that were tested in this study. The FSC (“free support choice”) trials refers to the first round of trials where the participant was given the freedom to choose their externally support strategy, if at all; meanwhile, OSC (“opposite support choice”) trials refers to the second round of trials, where the participant was required to either use or avoid using external support, based on their choice in the corresponding trial of the FSC (see Figure 23). Two task types are performed within four task hand Locations. For the task hand Locations, the height (a proportion of the participant’s height (H)) and horizontal reach (a proportion of the participant’s arm length (AL)) of the condition are indicated in brackets. The gross motor tasks were performed in six different orthogonal Directions, while the fine motor task was performed once within each Location.

Task Type	Force Direction	Task Hand Location							
		Low-Close (0.55H, 0.95AL)		Low-Far (0.55H, 1.2AL)		High-Close (0.75H, 0.95AL)		High-Far (0.75H, 1.2AL)	
External Support Choice		FSC	OSC	FSC	OSC	FSC	OSC	FSC	OSC
Gross Motor Task: Maximal Force Exertion	Superior	✓	✓	✓	✓	✓	✓	✓	✓
	Inferior	✓	✓	✓	✓	✓	✓	✓	✓
	Anterior	✓	✓	✓	✓	✓	✓	✓	✓
	Posterior	✓	✓	✓	✓	✓	✓	✓	✓
	Lateral	✓	✓	✓	✓	✓	✓	✓	✓
	Medial	✓	✓	✓	✓	✓	✓	✓	✓
Fine Motor Task: Precision		✓	✓	✓	✓	✓	✓	✓	✓

The participant completed a full round of 28 trials (every possible combination of hand Location and task hand exertion) for the first half of data collection. The first round consisted of “free support choice” (FSC) trials, where the participant was be granted the freedom to choose to externally support their body using any combination of, or none of, the available leaning or bracing surfaces. The second round of 28 trials consisted of “opposite support choice” (OSC) trials, during which the participant was instructed to utilize the opposite external support strategy to what was used for the same condition in the first round (Figure 23). More precisely, if the participant chose to use external support in the first round of trials (i.e. lean, brace, or lean and brace), she was asked to not use external support in the second round of trials. Conversely, if the participant chose not to use external support in the first round, she was then asked to use her “most natural” external support strategy in the second round to complete the task. There were therefore a total of 56 trials performed in this study for each participant. For both the FSC and OSC trial rounds, the physical experimental setup remained unchanged, including for trials where the participant was instructed not to externally support.

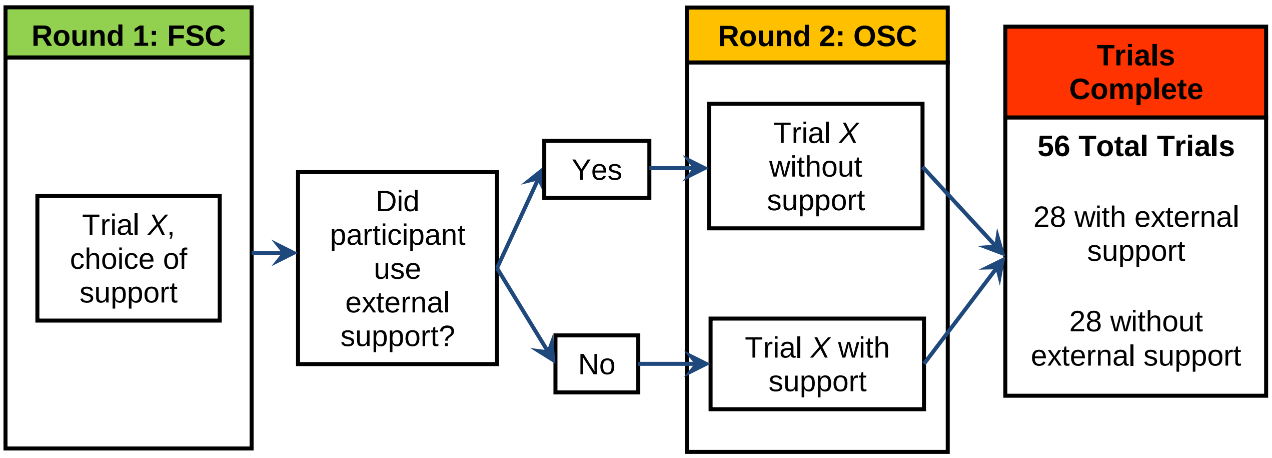


Figure 23: The flowchart above depicts how external support was controlled, for a given condition (Condition *X*), through the course of data collection. The first round consisted of FSC (free support choice) trials where there was no experimental control of external support use, thus participants were free to lean and/or brace as they choose. The second round consisted of OSC (opposite support choice) trials where the participant was instructed to do the opposite external support strategy as the corresponding trial in the first round. Thus, if they used external support in any way during the FSC trial, they were instructed to not use external support in the OSC trial, for a given condition.

Trial order was determined by a randomization block method. First, the order of the four task hand locations were decided, and then the six gross motor tasks and one fine motor task within that task hand location were performed in succession. However, the order of these gross and fine motor tasks were also be randomized within the task hand Location.

Figure 24 below shows two examples of a Jack digital human model simulating some of the postures and external support strategies that may be obtained by the participant during the trials, including use of the horizontal and vertical leaning surfaces, as well as the bracing surface at the thighs. Additionally, the model demonstrates the use of a split stance in one of the simulations (b).

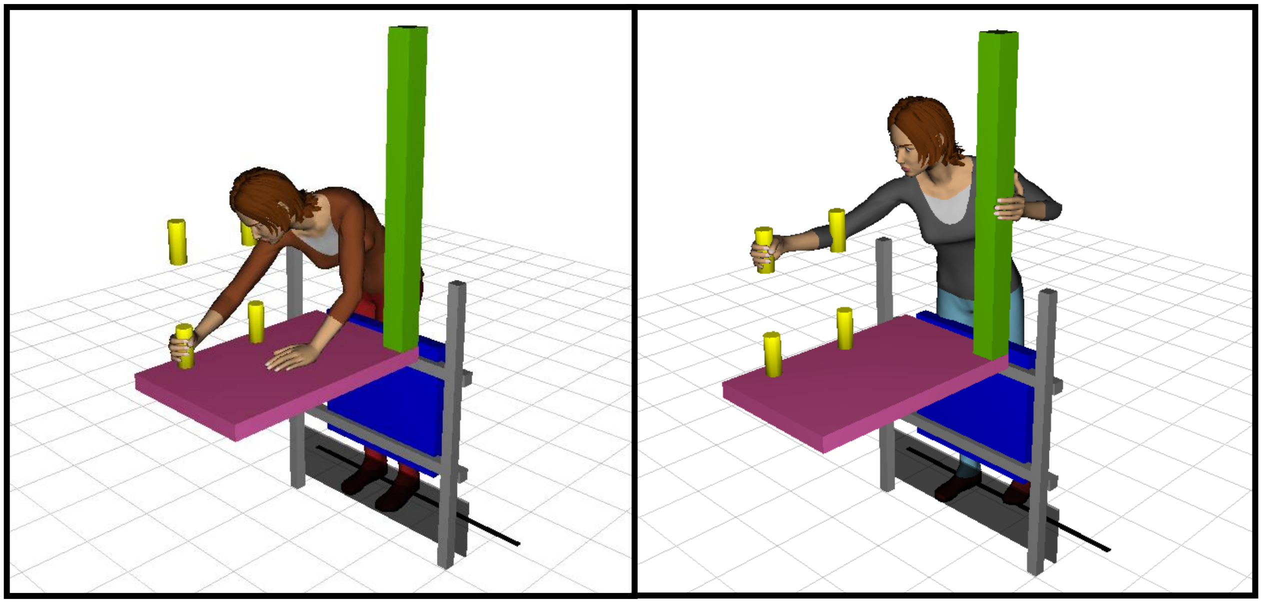


Figure 24: The above images show a 50th percentile female digital human manikin (Jack 8.0, Siemens Corporation, Ann Arbor, MI) performing two example conditions. The task hand Locations and external support surfaces have been adjusted to the correct proportions given the participant's height and arm length. The two conditions include; a) a gross motor, FSC trial at the Low-Far task hand Location, and b) a gross motor, FSC trial at the High-Far task hand Location. Note the use of the bracing surface, the vertical leaning surface, and the vertical leaning surface.

Overall, this experiment was designed to address limitations identified in previous studies of leaning and/or bracing. My thesis accounted for these limitations by: 1) providing participants with the choice to adjust their stance, 2) testing unconstrained external support conditions (including the option to lean and/or brace), 3) providing external support surfaces more representative of real automotive assembly scenarios, 4) controlling for the force direction in gross motor tasks, and 5) testing the effect of fine motor tasks on external support behaviours. A summary table comparing the conditions tested in my study is provided below (Table 4).

Table 4: Adapted from Table 1, this table summarizes the various task parameters and conditions from the three most relevant studies involving external support. Conditions and parameters included in this thesis are highlighted in green.
J: Jones (2012), C: Cappelletto (2013), F: Fewster (2013).

		Force Direction					
Task Hand Height	Task Hand Reach	Superior	Inferior	Anterior	Posterior	Lateral	Medial
High: ≥70% Stature	Close: 60%AL			J	J	J	J
	Medium: 90%AL		F	F	F		
	Far: >110%AL		F	F	F		
Medium: <70%, >50% Stature	Close: 60%AL	J		J	J	J	J
	Medium: 90%AL	C	C, F	F	C, F		
	Far: >110%AL	C, J	C, F	F, J	C, F, J	J	J
Low: ≤50% Stature	Close: 60%AL	J		J	J	J	J
	Medium: 90%AL	C	C		C		
	Far: >110%AL	C	C		C		

		Cappelletto (2013)	Fewster (2013)	Jones (2012)	Liebregts (2014)
External Support	Leaning Only		✓	✓	
	Bracing Only	✓		✓	
	Leaning and Bracing			✓	
	Choice: Leaning and/or Bracing				✓
	None	✓	✓	✓	✓
Force Level	Maximal			✓	✓
	Submaximal	✓	✓		
	Precision				✓
Available Surfaces	Vertical Hip/Thigh Bracing	✓		✓	✓
	Horizontal Hand Leaning		✓	✓	✓
	Vertical Hand Leaning		✓		✓
Stance	Constrained	✓	✓		
	Unconstrained			✓	✓

3.4 Data Processing

All kinetic data from the three load cells were filtered using a half-second moving average filter. For the gross motor task trials, I selected the frame that corresponded with the peak force exerted by the participant's task hand during their maximal exertion. For the fine motor task trials, I observed the force-time history of the trial and identified the start and end frames. I then selected the middle frame between these two time points for kinematic analysis.

For kinematic data processing, motion capture data from Cortex were streamed into Jack 8.0.1 digital human modelling software (Siemens Corporation, Ann Arbor, MI) using the Motion Analysis module. A digital female manikin, with the same anthropometric measures as the participant, was synced to match the posture at the aforementioned time frames. A task hand force vector, with a direction and magnitude equivalent to that of the given trial, was applied to the manikin's task hand. Conversely, if applicable, a leaning force vector, with a direction and magnitude equivalent to that of the given trial, was applied to the manikin's leaning hand. From this process, I used the ForceSolver module (Figure 25) to record the following outcome measures: 1) right and left shoulder flexion/extension, abduction/adduction, and humeral rotation angles and moments, 2) trunk flexion/extension, lateral bend, and axial twist angles and moments, 3) elbow flexion/extension angle and moment, and 4) resultant L5/S1 compression.

For the kinetic data processing, different methods were used to extract variables dependent on the task type being analyzed. First, force Directions and magnitudes associated with external support were determined. For bracing, the resultant force was derived from calculating the Euclidean norm based on the F_x, F_y, and F_z force components from the load cell. The center of pressure (CoP) was used to determine the bracing location. If leaning was used by the participant, the resultant force was derived from calculating the Euclidean norm based on the F_x, F_y, and F_z force components from the leaning load cell, while the leaning location was determined by noting the vertical and horizontal position of the left hand marker. For the gross motor tasks (maximal forces), the kinetic data, from the load cells at the frame of peak task hand force, were extracted for analysis. For the fine motor task, the kinetic data were averaged between the start and end frames of the effort. These frames were also used to record the time to completion for the fine motor tasks.

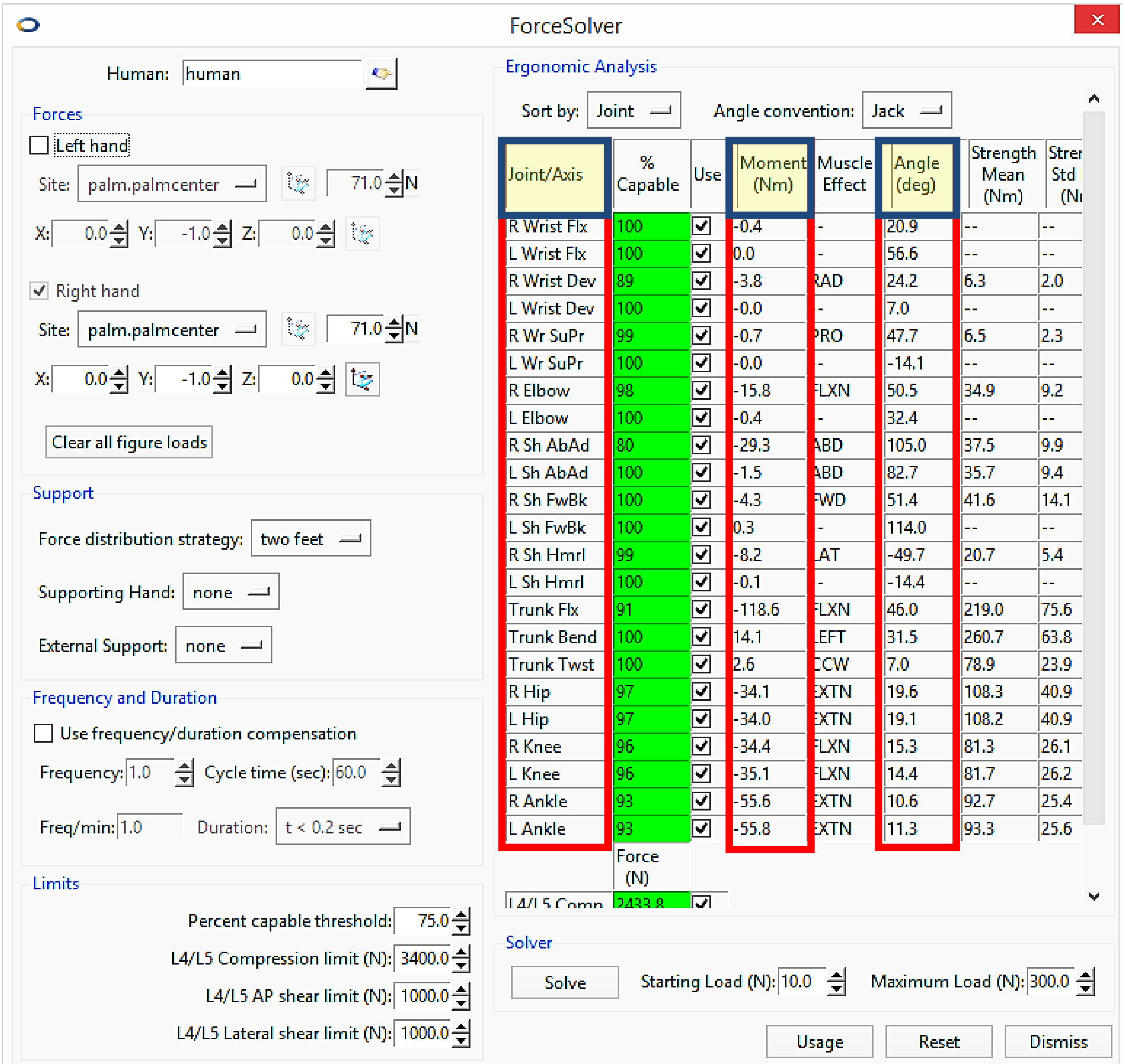


Figure 25: A sample window of the Jack 8.0.1 ForceSolver output module. The three main output categories are highlighted in yellow in the blue boxes, while the red boxes outline the listed joints and corresponding moment and angle values.

Resultant angles and moments were also calculated. For the shoulder, the resultant angle was calculated as the resultant from the shoulder abduction/adduction and forward/back angles, while the resultant moment was calculated as the resultant of the three moments about the shoulder (forward/back, abduction/adduction, and humeral rotation). Meanwhile, the trunk resultant moment was calculated as the resultant of the three moments about the trunk (axial twist, lateral bend, flexion/extension).

3.5 Statistical Analysis

All statistical computations were performed using IBM SPSS Statistics 20 software (IBM, Chicago, IL). These analyses were used to answer a series of inquiries. The structures of the ANOVAs performed are found in Appendix C.

For all statistical analyses, significance was determined by a $p < 0.05$.

3.5.1 Predicting External Support Behaviours

A logistical regression analysis was performed to predict external support behaviours. Using a series of inputs, three equations were developed to predict: 1) the use of leaning, 2) the use of bracing, and 3) the simultaneous use of leaning and bracing. All models were developed with data from the free support choice (FSC) trials (n = 504). The inputs included individual characteristics of participant mass, stature and arm length, as well as participant strength measures (shoulder flexion, extension, adduction and abduction; elbow flexion and extension; trunk flexion and extension, and handgrip). Inputs also included task characteristics: force direction (Anterior [-1]/Posterior [+1] code, Superior [-1]/Inferior [+1] code, Lateral [-1]/Medial [+1] code), task hand vertical height, and task hand horizontal reach. When forces were in one direction (e.g. Anterior = -1), the other codes were set to zero (e.g. Superior/Inferior and Lateral/Medial). For Precision tasks, all 3 codes were set to zero. A stepwise regression procedure was used, and outputs <0.5 were changed to “0” and those ≥0.5 were changed to “1”. A fourth method predicted simultaneous leaning and bracing by adding the binary values from the lean equation and the brace equation.

3.5.2 External Support Behaviours

To analyze the external support behaviours, descriptive statistics were used to compare the 28 conditions involving external support. The independent variables included task hand Location (n = 4) and Direction (n = 7; included fine motor task), while the dependent measures were the percentage of participants using: external support (any kind), leaning, bracing, leaning only, bracing only, and simultaneous leaning and bracing. For trials where leaning was present, the percentage of participants leaning on the horizontal and vertical surfaces were compared, as were the vertical and horizontal leaning hand positions (relative to participant height), for each condition.

3.5.3 Effect of External Support, Location and Direction on Task Hand Force

A 2x4x6 repeated measures ANOVA was performed to determine the influence of external support and task characteristics on task hand force magnitude. The independent variables included: 1) external Support use (n = 2), 2) task hand Location (n = 4), and 3) task hand exertion Direction (n = 6).

3.5.4 Effects of External Support on Task Arm and Trunk Joint Loading and Posture

For the task arm and trunk, a 2x4x6 repeated measures ANOVA was performed to determine the influence of external support, and task characteristics, on kinematics and kinetics. Since the Precision tasks were not included, these three-way analyses were based on the 48 maximum exertion conditions. The independent variables included: 1) external Support use (n = 2), 2) task hand Location (n = 4), and 3) task hand exertion Direction (n = 6). The dependent variables included: 1) resultant shoulder angle (task arm), 2) resultant shoulder moment (task arm), 3) elbow flexion angle (task arm), 4) elbow moment (task arm), 5) trunk resultant moment, 6) trunk axial, and 7) trunk lateral angle.

3.5.5 Effect of Location and Direction on External Support Kinetics

For the support conditions, participants could choose to lean only, brace only or lean and brace simultaneously. Thus, there were an unequal number of occurrences, for each of the three possibilities for each combination of Location and Direction. As such, repeated measures ANOVAs were not possible and descriptive statistics were calculated to determine mean leaning and/or bracing forces for each combination of: 1) task hand Location (n =4), and 2) Direction (n = 7; included fine motor task).

3.5.6 Effect of Location and Direction on Leaning Arm Joint Posture and Loading

For the same reason described in section 3.5.5, descriptive statistics were calculated to determine means for: 1) elbow flexion angle (leaning arm), 2) elbow moment (leaning arm), 3) resultant shoulder angle (leaning arm), and 4) resultant shoulder moment (leaning arm), for the different combinations of: 1) task hand Location (n = 4) and 2) Direction (n = 7; included fine motor task).

3.5.7 Fine Motor Task Analyses

For the fine motor tasks, the variables associated with the task arm were analyzed. A 2x4 repeated measures ANOVA was performed for just the fine motor task conditions. The independent variables were Support (n = 2) and task hand Location (n = 4), while the dependent measures included: 1) elbow flexion angle (task arm), 2) shoulder resultant angle (task arm), 3) trunk axial angle, 4) trunk lateral angle, 5) trunk resultant moment, and 6) time to complete task.

3.5.8 Post-Hoc Procedure

Significant effects were further analyzed using a post hoc procedure involving Tukey's Honestly Significant Difference (HSD). For main effects, the K value was equal to the number of levels for the independent variable was used to calculate Tukey's HSD. For example, if I were to compared the Supported vs. Non-Supported main effect (two levels), I would use K = 2 to calculate an HSD. For interaction effects, I counted the number of "unconfounded comparisons" for a given analysis and applied the Cicchetti (1972) correction to determine an adjusted K value (Figure 26). An unconfounded comparison is described as a comparison between two means that have commonality among at least one level of an independent variable. Given that the Tukey HSD was originally developed for main effects, this method corrects the k so that it does not overestimate the K value and, thus, does not increase the HSD value unnecessarily. To determine the number of unconfounded comparisons, I first decided which mean comparisons were of most interest in my analysis. For instance, in a 2x4 analysis comparing a variable within two levels of support and four levels of task hand Locations, I was more interested in the comparison of means between the two levels of Support, than the effect of hand Location. Therefore, for this example, I based my Cicchetti's adjusted K value on the four unconfounded comparisons that would be made between the Support conditions at each hand Location (n = 4, K = 3.052), and ignored the 6 comparisons that could have been made for both Support conditions (n = 12, K = 6.048).

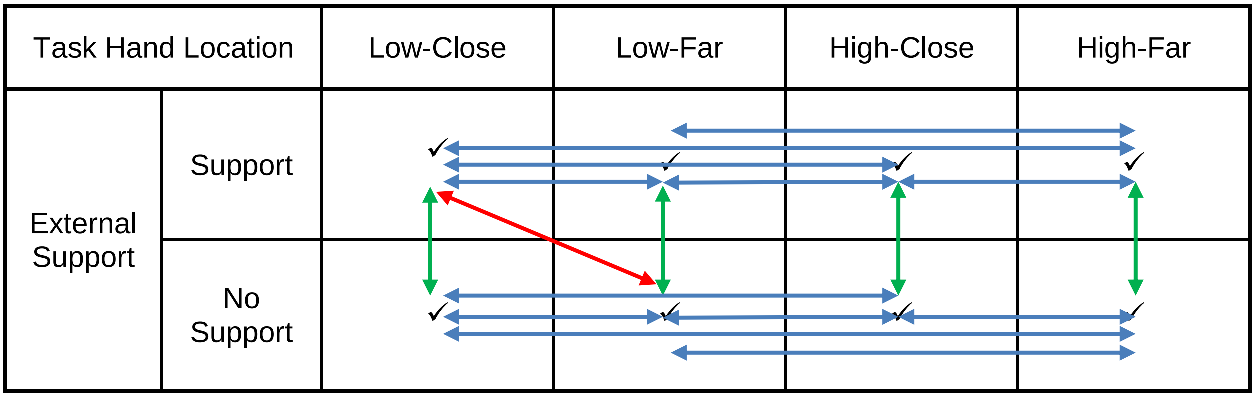


Figure 26: This figure illustrates the post hoc procedure used to select an adjusted K value for the calculation of Tukey's HSD for interaction effects, based on Cicchetti (1972). A sample 2x4 analysis is shown. The number of unconfounded comparisons (blue and green arrows) was determined, based on pertinence to the research question being answered by the analysis. For instance, a study more concerned with the effects of external Support would choose four unconfounded comparisons (green arrows). This would result in a Cicchetti's adjusted K value of 3.052 for the calculation of Tukey's HSD. The diagonal red arrow shows an example of a confounded comparison, which were considered to be irrelevant in my study.

4.0 RESULTS

For all ANOVAs, only main effects and interactions with $p < 0.05$ and an Eta-squared value greater than or equal to 1.0% ($\eta^2 \geq 1.0\%$) are presented. These effects are considered both statistically significant and functionally relevant, as they accounted for at least 1% of the total variability (sums of squares) for a given dependent variable (Murphy & Myors, 2004). In addition, since the primary focus of my thesis was the effects of external Support, the majority of findings presented here involve the highest order significant effect involving external support. The effects meeting the above criteria, but not including external Support, can be found in Appendix E. Participant anthropometry and strength data can be found in Appendix D. No participant data were excluded from the statistical analyses.

4.1 Prediction and Changes in External Support Behaviours

4.1.1 Logistic Regression Equations to Predict External Support Behaviours

The first regression model was able to correctly predict the occurrence of bracing for 79.8% of the FSC trials, while explaining 30.4% of the variability in the data (Table 5). Significant predictors included individual characteristics (participant body mass, handgrip strength, elbow flexion strength, elbow extension strength, shoulder flexion strength, shoulder abduction strength and shoulder adduction strength) and task characteristics (task hand horizontal reach, Anterior/Posterior code, Superior/Inferior code, and task hand force).

The second model was able to correctly predict leaning occurrence for 86.3% of the cases, while explaining 34.0% of the variance (Table 5). Significant predictors included individual characteristics (participant stature, body mass, arm length, elbow extension strength, shoulder flexion strength, shoulder extension strength, shoulder abduction strength, shoulder adduction strength) and task characteristics (task hand vertical height, task hand horizontal reach, task hand force, Anterior/Posterior code, Superior/Inferior code, and Lateral/Medial code).

The third, and final, logistic regression model aimed to predict when both leaning and bracing would occur simultaneously, and was correct for 74.2% of the cases while explaining 24.3% of the variance in the data (Table 5). Significant predictors included individual characteristics (participant height, arm length, handgrip strength, elbow flexion strength, shoulder flexion strength, shoulder abduction strength) and task characteristics (task hand horizontal reach, Anterior/Posterior coding, Superior/Inferior coding, and task hand force).

The fourth and final method, which was developed for predicting simultaneous leaning and bracing by adding the binary regression results from the first two models, was able to correctly predict simultaneous leaning and bracing in 74.2% of all cases (Table 5).

Table 5: The table below shows the logistic regression summaries for the three models, predicting 1) simultaneous leaning and bracing, 2) leaning, and 3) bracing. First, R^2 values and percentage of correct prediction are presented. Next, intercept values and beta coefficients associated with significant inputs for the given model are presented. Greyed-out boxes represent insignificant inputs for a given model.

	Simultaneous Lean & Brace	Leaning	Bracing
R^2	**0.243**	**0.340**	**0.304**
%Correct	**74.2%**	**86.3%**	**79.8%**
Intercept	-1.14398	-0.27955	-0.32112
Height (cm)	0.02374	0.02915	
Body Mass (kg)		-0.00451	0.00431
Arm Length	-0.04480	-0.05776	
Handgrip Strength	0.00226		0.00312
Elbow Flexion Strength	-0.01884		-0.03034
Elbow Extension Strength		-0.01975	0.01510
Shoulder Flexion Strength	-0.01297	-0.00326	-0.01335
Shoulder Extension Strength		0.00233	
Shoulder Abduction Strength	0.02106	0.01326	0.01459
Shoulder Adduction Strength		0.00419	-0.00380
Trunk Flexion Strength			
Trunk Extension Strength			
Task Hand Height (/Ht)		-0.15680	
Task Hand Reach (/AL)	0.50311	0.29068	0.56279
Anterior (-1) Posterior (1)	0.12827	-0.02699	0.13892
Superior (-1) Inferior (1)	-0.10257	-0.05177	-0.07291
Lateral (-1) Medial (1)		-0.02619	
Task Hand Force	0.00091	0.00180	0.00016

4.1.2 Changes in External Support Behaviours

Of the FSC trials (n = 504), some form of external support was employed between 93.1 - 100.0% for the maximal hand force trials (depending on the Direction), while the fine motor Precision task had a much lower overall prevalence of external support (52.8%). For five of the seven hand tasks, simultaneous leaning and bracing was the most prevalent external support strategy, accounting for 62.5 - 81.9% of FSC trials. The exceptions were Anterior (52.8% only leaning) (Figure 29), and Precision task (47.2% only bracing) (Figure 29).

In general, leaning behaviours were highly prevalent for all gross motor tasks and hand Locations (94.0%, pooled across all gross motor tasks and hand Locations) (Figure 27). Within the gross motor tasks, Low-Far had the highest leaning frequency (97.2%), while Low-Close had the lowest (89.8%). In contrast, the Precision task had a very low incidence of leaning (19.4%), however, similar to the gross motor tasks, Low-Far had the highest frequency of leaning (50.0%).

Bracing was much less prevalent than leaning behaviours for the gross motor tasks, occurring in 72.2% of all FSC cases (Figure 28). Bracing was most prevalent for the Lateral, Medial, and Superior efforts (84.7%, 86.1%, 83.3%, respectively). Meanwhile, the two “Far” Locations (i.e. High-Far and Low-Far) had the highest frequencies of bracing for all Directions but the Anterior effort, where bracing was much less prevalent (40.3%). Furthermore, the Low-Close and Low-Far actually had the highest prevalence for the Anterior effort (50.0% each). Compared to leaning, the Precision task had a much higher frequency of bracing (47.2%), while the two “Far” hand locations had the highest prevalence within this hand task (72.2% and 61.1% for High-Far and Low-Far, respectively).

For the two exclusive strategies, leaning only frequencies exceeded bracing only for all gross motor tasks (Figure 29). In absolute terms, leaning only exceeded bracing only by an average of 21.8% across all gross motor tasks. The largest discrepancy between the two strategies was for the Anterior effort, where there was 52.8% leaning only compared to 4.2% bracing only. In contrast, the Precision task had 41.6% more bracing only than leaning only.

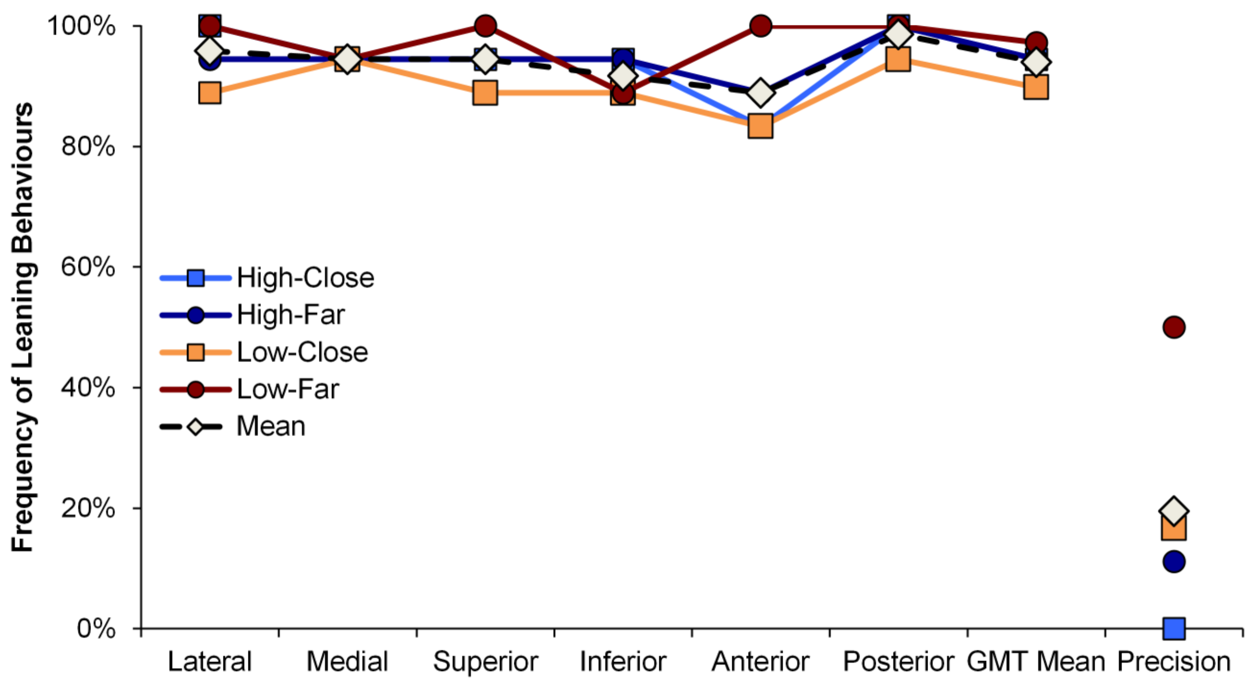


Figure 27: Descriptive statistics showing the average frequency (n = 18) of leaning for the different combinations of hand Location and effort Direction for all FSC (“free support choice”) trials. Each line represents a given hand location. GMT: gross motor task.

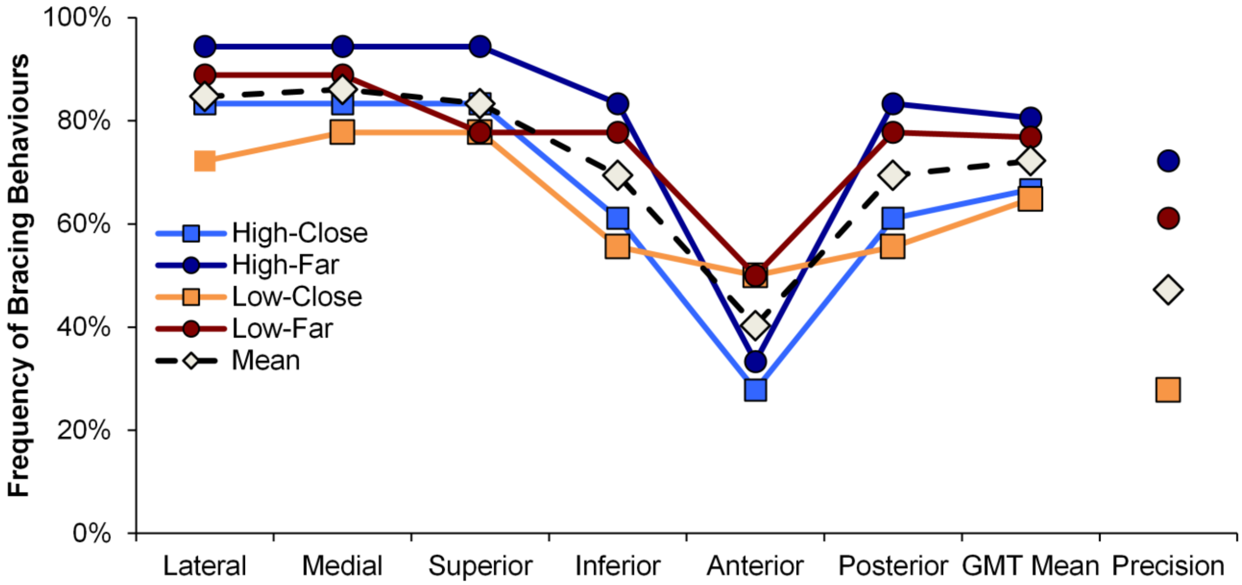


Figure 28: Descriptive statistics showing the average frequency (n = 18) of bracing for the different combinations of hand Location and effort Direction for all FSC (“free support choice”) trials. Each line represents a given hand location. GMT: gross motor task.

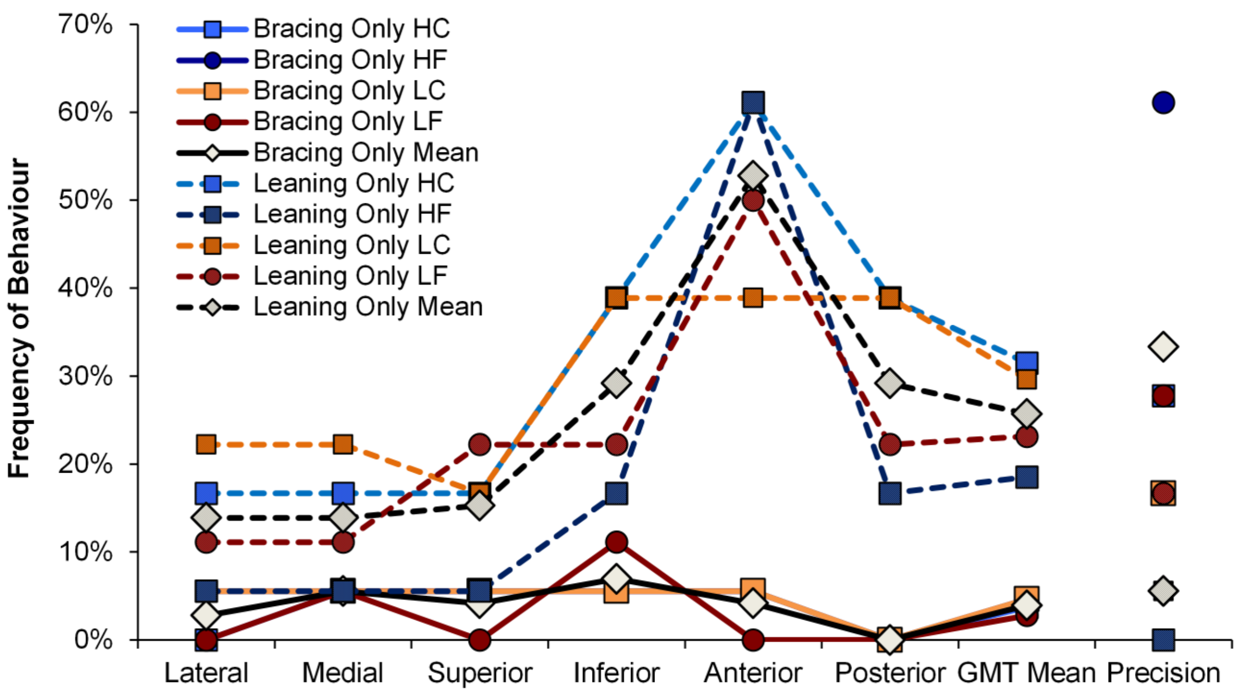


Figure 29: Descriptive statistics showing the average frequency (n = 18) of leaning only, and bracing only behaviours for the different combinations of hand Location and effort Direction for all FSC (“free support choice”) trials. Each line represents a given hand location. HC: High-Close, HF: High-Far, LC: Low-Close, LF: Low-Far.

4.1.3 Leaning Surface Usage and Relative Hand Positioning

For all cases where leaning was present (FSC and OSC trials, n = 441), the leaning surface usage, and relative vertical and horizontal hand positions, were analyzed (Figure 30). When comparing between different exertions (Figure 30 a)), Posterior and Anterior efforts had the highest frequency of vertical surface usage at 75.0% and 69.7%, respectively. Meanwhile, Superior and Inferior efforts had the highest frequency of horizontal surface usage at 62.3% and 62.7%, respectively. For the Precision task, the horizontal surface was preferred 60.7% of the time. When the vertical surface was used, the average vertical hand position (relative to participant height) was always between 66.8 and 71.2% of stature (mean = 69.6%). Similar to vertical hand position, the horizontal hand Location (relative to participant height), was also quite consistent across all hand tasks, ranging between 23.1 and 29.0% of stature (mean = 26.4%).

When comparing leaning hand Locations, across different task hand location conditions (Figure 30 b)), the “Close” hand locations (High-Close and Low-Close) had the highest frequency of vertical surface usage at 68.5% and 58.7%, respectively, while High-Far had slightly less at 55.1% frequency. Conversely, the Low-Far hand location was predominantly associated with leaning on the horizontal surface (66.4%). Similar to the above-mentioned hand task comparison, the vertical and horizontal hand placements were relatively consistent across all task hand Locations.

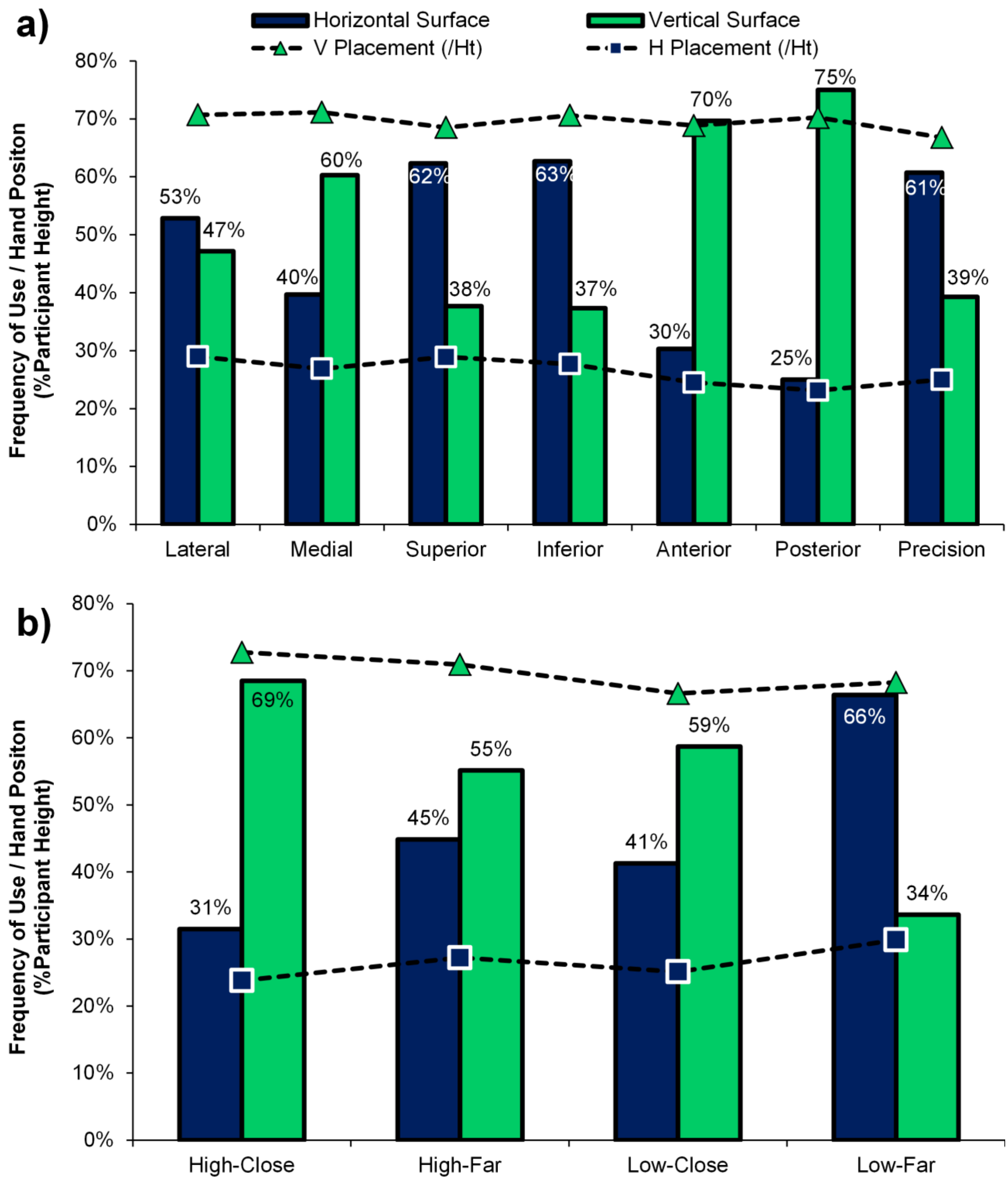


Figure 30: Descriptive statistics showing the frequency of leaning hand surfaces usage for trials with leaning present (n = 441), sorted by; a) effort Direction, and b) task hand Location. Each bar represents the frequency of trials when the vertical surface (green) or horizontal surface (blue) was used. The green line graph shows the mean vertical hand placement when the vertical surface was used, while the blue line graph shows the mean horizontal hand placement when the horizontal surface was used (relative to participant height).

The results of the relevant ANOVAs are summarized in Table 6.

4.2 Task Hand Force for the Gross Motor Tasks

There was an interaction between Direction and Support on maximum task hand force (Figure 31). Supported conditions were higher than No Support for each Direction. In addition, Supported conditions were significantly higher for each Direction, except Anterior and Inferior. On average, the hand force values with Support were 64.8% (68.6 N) greater than those without. The following ranks the relative, increases from No Support to Supported, from least to greatest (absolute increases provided in parentheses): Anterior at 2.7% (6.3 N), Inferior at 32.6% (43.0 N), Posterior at 84.6% (149.3 N), Lateral at 85.9% (62.7 N), Superior at 91.3% (65.2 N), and Medial at 119.7% (85.1 N).

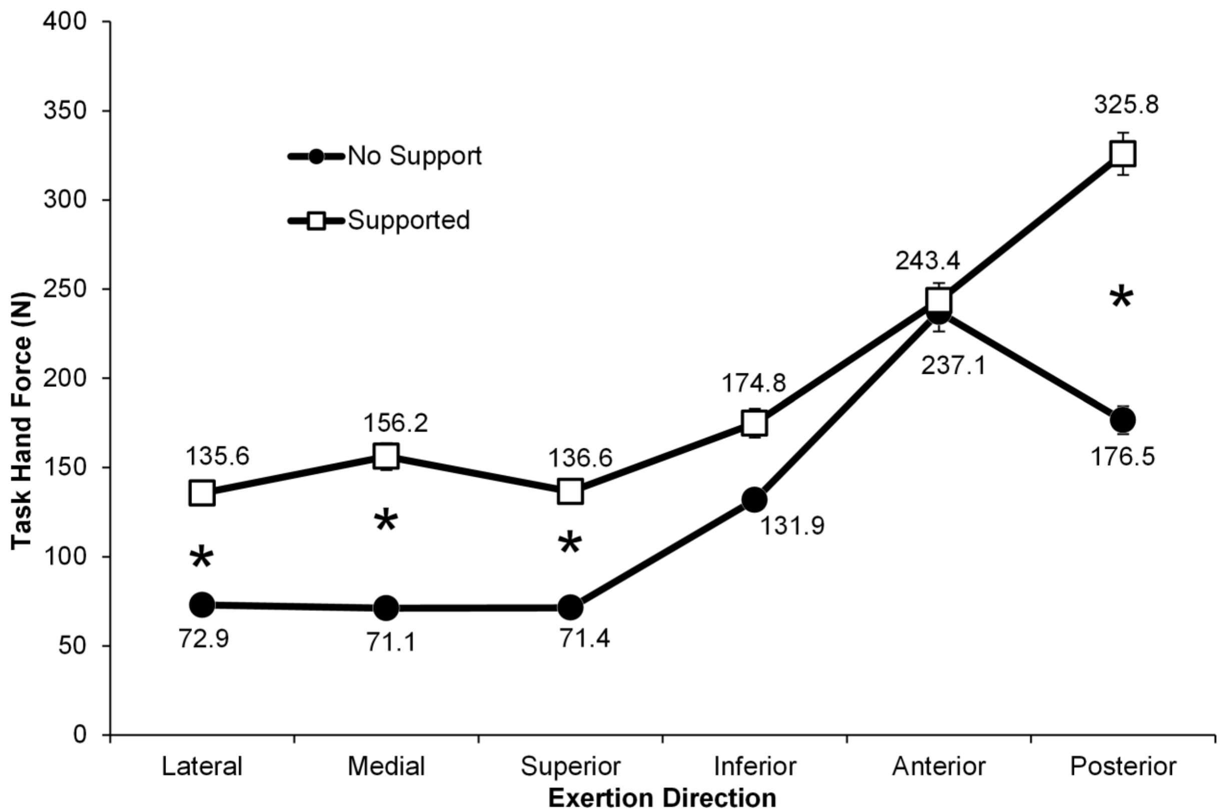


Figure 31: The interaction between Direction and Support on task hand force. Mean values and standard error bars are shown. Significant differences between Supported and Non-Supported values are denoted by an asterisk.

Table 6: A summary list of all the p-values and their associated η^2 values (in brackets) from the ANOVA analyses associated with the gross motor tasks (i.e. Precision task excluded). The table shows the results from the 2x4x6 repeated measures ANOVA with External Support Presence ("Support"), Task Hand Location ("Hand Location"), and Task Hand Exertion Direction ("Direction") as independent variables. The independent variables are listed on the top row of the table with main effects, two-way, and three-way interactions shown. Dependent variables are listed in the left-most column. Per the Legend, cells in green indicate significant p-values (sorted into three categories), while values with red strikethrough text represents outcomes associated with a $\eta^2 < 0.01$ (negligible effect size). Cells highlighted in blue are the highest-level effects that will be presented in this chapter.

Variable	Support (n=432)	Hand Location (n=216)	Direction (n=144)	Support * Location (n=108)	Support * Direction (n=72)	Location * Direction (n=36)	Support * Location * Direction (n=18)
Task Hand Force	**0.0001 (0.125)**	~~**0.0001 (0.007)**~~	**0.0001 (0.410)**	~~0.2764 (0.001)~~	**0.0001 (0.050)**	**0.0001 (0.016)**	~~**0.0001 (0.008)**~~
Task Elbow Flexion Angle	**0.0001 (0.181)**	**0.0001 (0.052)**	**0.0001 (0.348)**	~~0.0306 (0.003)~~	**0.0001 (0.029)**	**0.0001 (0.011)**	**0.0001 (0.011)**
Task Elbow Moment	~~0.1670 (0.002)~~	~~**0.0006 (0.007)**~~	**0.0001 (0.396)**	~~0.1286 (0.002)~~	**0.0001 (0.041)**	**0.0001 (0.040)**	**0.0001 (0.024)**
Task Shoulder Resultant Angle	0.0065 (0.014)	**0.0001 (0.118)**	**0.0001 (0.183)**	**0.0002 (0.014)**	~~0.1689 (0.004)~~	**0.0001 (0.029)**	~~0.1865 (0.005)~~
Task Shoulder Resultant Moment	~~0.5059 (0.001)~~	~~0.0050 (0.009)~~	0.0116 (0.032)	~~0.5017 (0.001)~~	0.0017 (0.028)	**0.0001 (0.043)**	0.1700 (0.013)
Trunk Axial Angle	0.0017 (0.028)	**0.0001 (0.040)**	0.0118 (0.024)	~~0.0022 (0.001)~~	**0.0001 (0.069)**	**0.0001 (0.028)**	0.0018 (0.014)
Trunk Lateral Angle	~~0.3189 (0.002)~~	**0.0001 (0.030)**	**0.0001 (0.105)**	**0.0001 (0.027)**	0.0019 (0.021)	0.0449 (0.014)	0.0072 (0.014)
Trunk Resultant Moment	~~0.6870 (0.000)~~	~~0.0196 (0.007)~~	**0.0001 (0.126)**	0.0028 (0.014)	**0.0004 (0.025)**	**0.0001 (0.038)**	0.2345 (0.011)

Legend
To be presented and/or discussed
~~η2 < 1%~~
p < 0.001
p < 0.01
p ≤ 0.05
p > 0.05

4.3 Effects of External Support Joint Loading and Posture for Gross Motor Tasks

4.3.1 Task Arm Elbow Flexion Angle and Moment

There was a three-way interaction between Support, Location, and Direction on task arm elbow flexion angle (Figure 32). Supported angles were higher than Non-Supported for all combinations of Location and Direction, except Anterior in the High-Close and High-Far Locations, and Posterior in the Low-Far task location. On average, elbow flexion angles associated with external Support were higher by an average of 30.8˚.

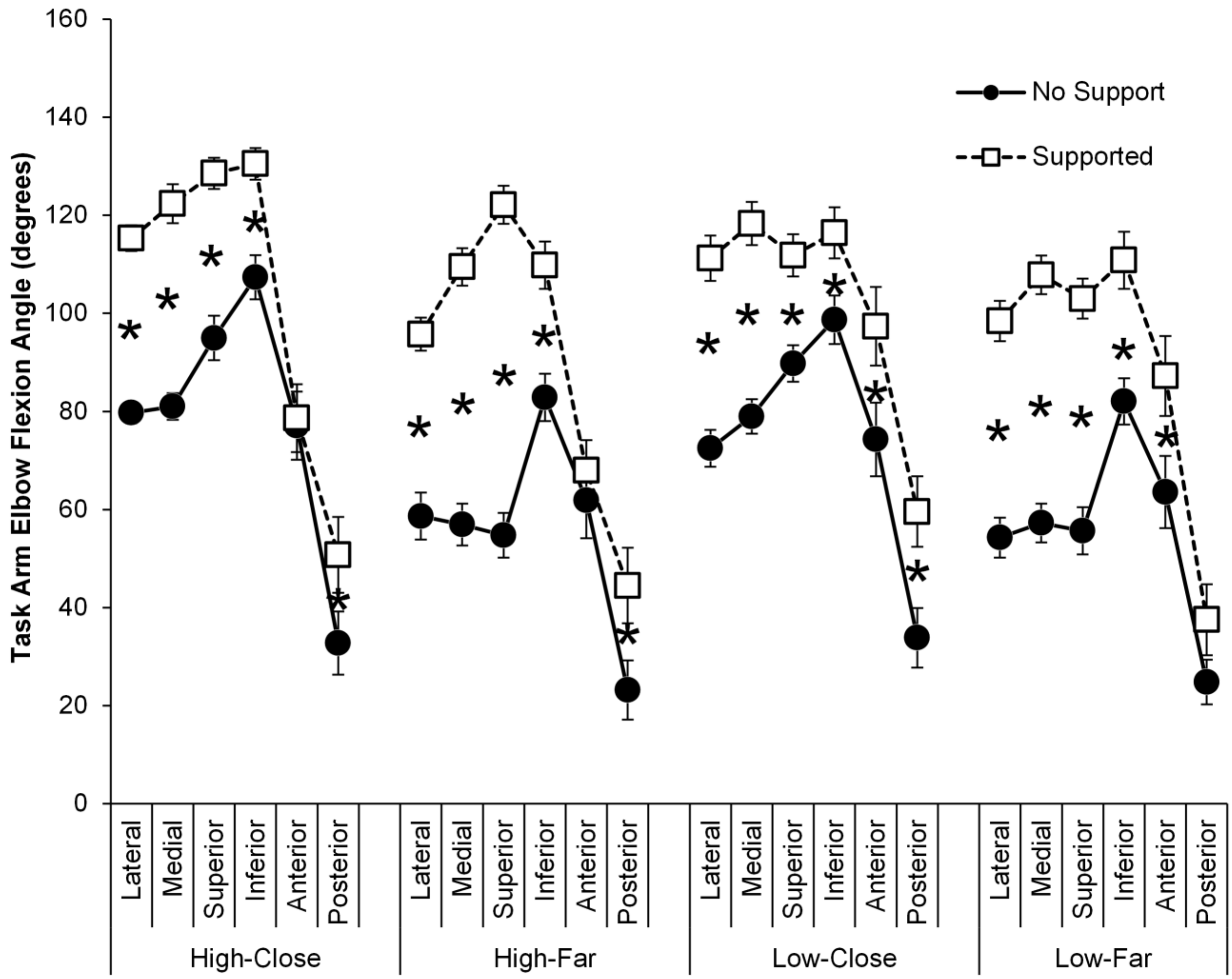


Figure 32: The three-way interaction between Support, Location, and Direction, on task arm elbow flexion angle. A straight arm is represented by 0˚ flexion. Significant differences are denoted with an asterisk ($p < 0.05$). Mean values and standard error bars are shown.

There was also a three-way interaction between Support, Location, and Direction on task arm elbow moment (Figure 33). For the two “High” hand locations (High-Close and High-Far), the Supported Posterior efforts showed significantly greater moments than with No Support (by 19.5 and 26.5 Nm, respectively). For the “low” task hand locations (Low-Close and Low-Far), the supported Superior and Anterior exertion directions showed significantly greater moments than No Support.

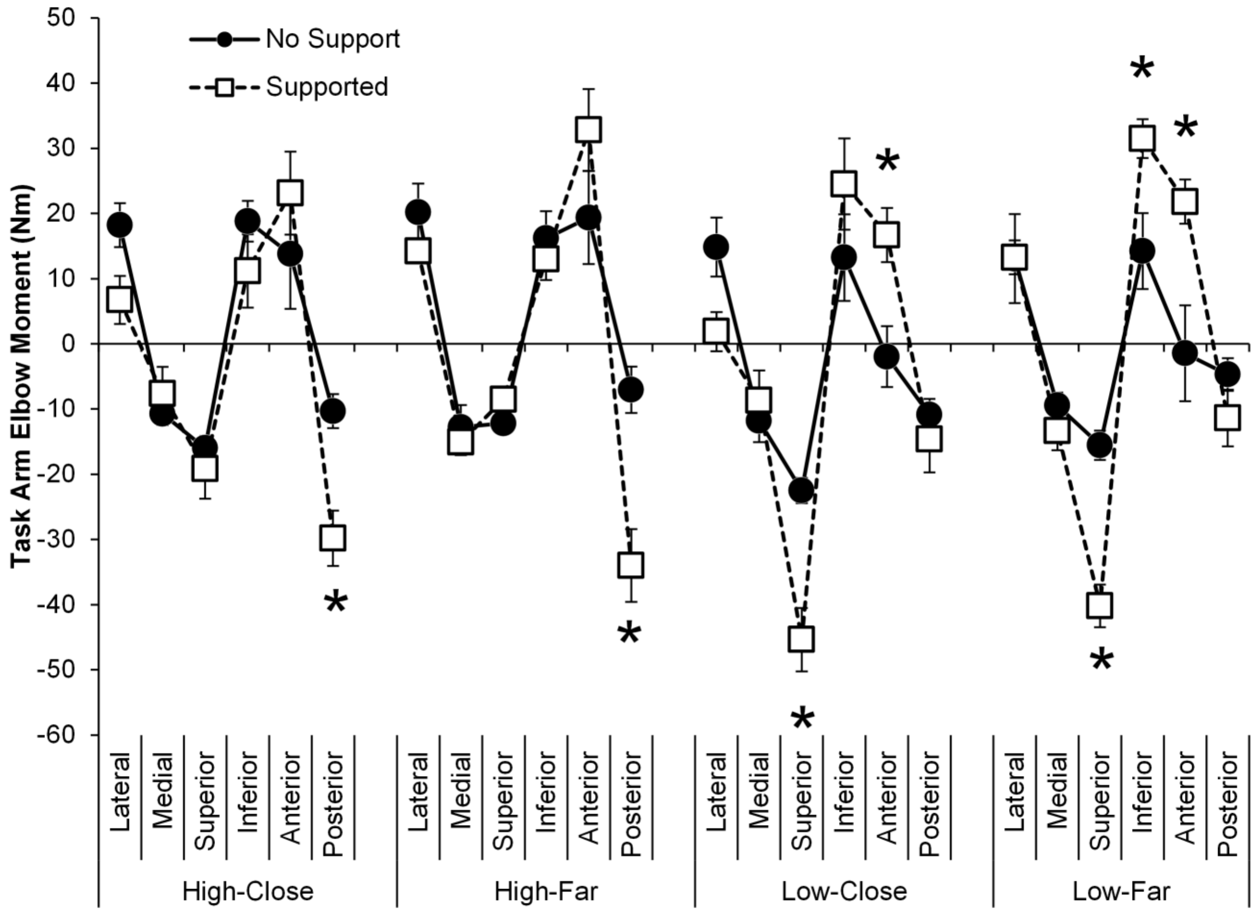


Figure 33: The 3-way interaction between Support, Location, and Direction, on task arm elbow moment. Elbow flexors cause positive moments, with extensors causing negative moments. Significant differences are denoted with an asterisk ($p < 0.05$). Mean values and standard error bars are shown.

4.3.2 Task Arm Resultant Shoulder Angle and Moment

There was a significant interaction between Support and Location on task arm resultant shoulder angle. However, post hoc analysis showed that there were no significant differences between the means associated with and without Support.

There was a significant interaction between Support and Direction on resultant shoulder moment. However, again, the post hoc analysis found no significant differences between the means associated with and without external support.

4.3.3 Trunk Angles and Moments

There was a significant three-way interaction between Support, Location, and Direction on trunk axial twist angle (Figure 34). For all task hand Location, the Supported Lateral exertion Directions were significantly different than those with No Support. For the High-Close, High-Far and Low-Far task hand locations, the Posterior Directions had significant differences, with the Supported trials having positive angles (twisting to the left) and the Non-Supported trials having negative angles (twisting to the right). For the two “High” task hand Locations, the Non-Supported Medial Directions had significantly greater negative values than those with Support.

There was also a three-way interaction between Support, Location, and Direction on trunk lateral angle (Figure 35). For the High-Far hand Location, the only significant difference was within the Lateral Direction, where the angles with external Support were large and negative (negative angles represent a bend to the right), while those without external Support were positive (a bend to the left). For the “Low” task hand Locations (Low-Close and Low-Far), the Medial and Posterior efforts with Support were significantly higher than No Support. Finally, the trunk lateral angle with Support, for the Inferior Direction within the Low-Close task hand Location, was significantly greater than No Support.

For the trunk resultant moment, there were interactions between Support and Location, as well as Support and Direction. However, for both interaction effects, there were no significant differences between Support and No Support at any Location, or in any Direction.

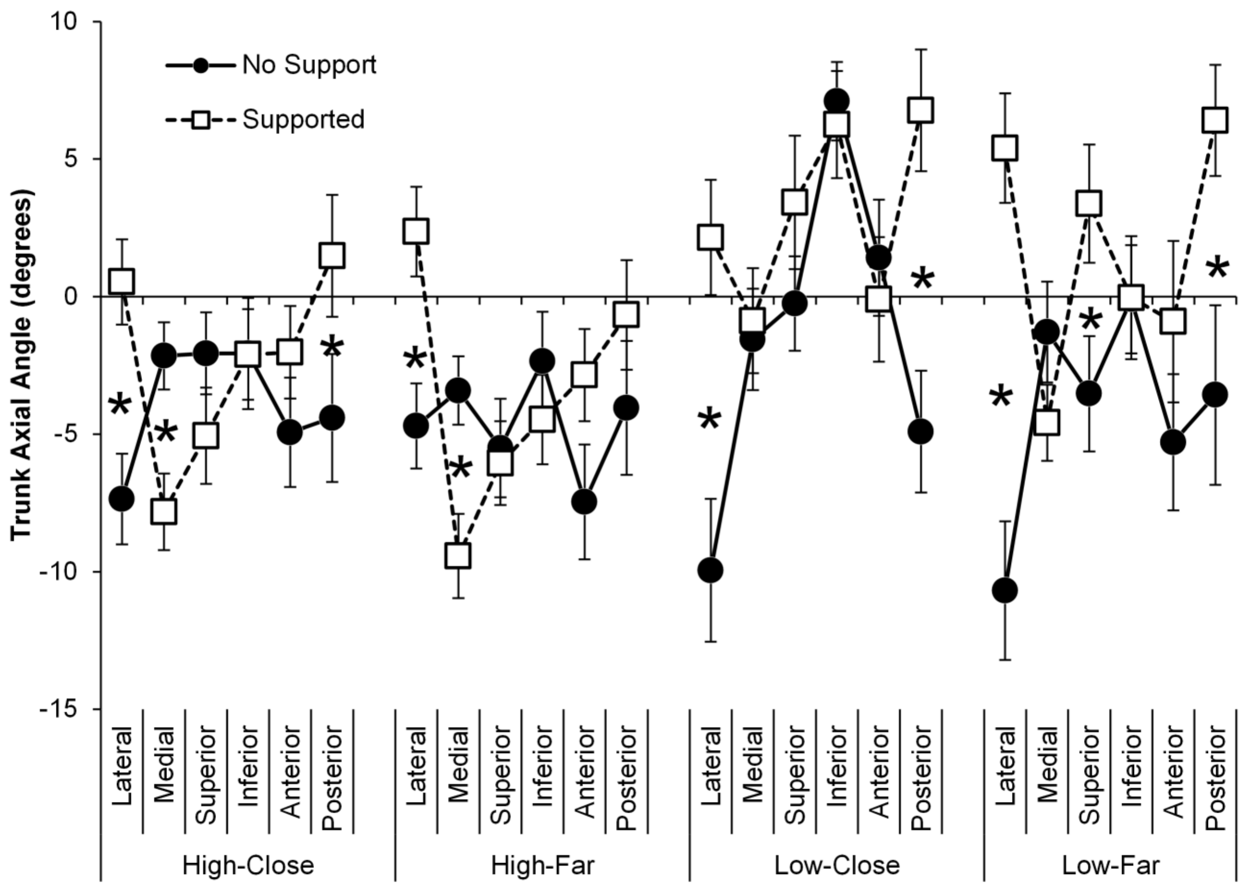


Figure 34: The three-way interaction between Support, Location, and Direction on trunk axial twist angle. A positive angle represents a twist to the left, while a positive angle represents a twist to the right. Significant differences are denoted with an asterisk ($p < 0.05$). Mean values and standard error bars are shown.

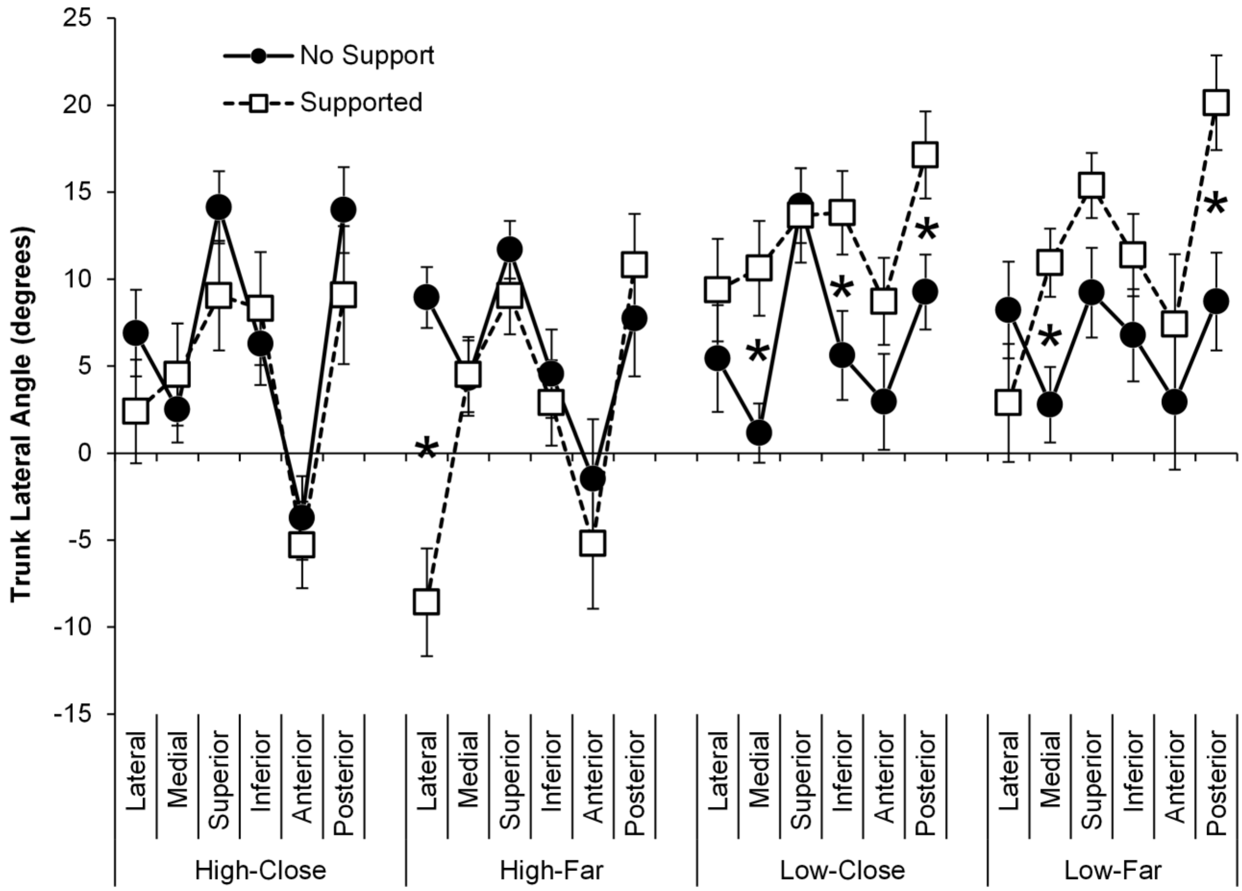


Figure 35: The three-way interaction between Support, Location, and Direction on trunk lateral angle. A positive angle represents a lateral bend to the right, while a negative angle represents a lateral bend to the left. Significant differences are denoted with an asterisk ($p < 0.05$). Mean values and standard error bars are shown.

4.4 Effect of Location and Direction on External Support Kinetics

Descriptive statistics were used to compare resultant bracing and leaning forces between combinations of task hand Location and Direction. Mean values for each measure were obtained, based only on trials which featured bracing (n = 311) and leaning (n = 441).

Resultant bracing force appeared to change across the different tasks (Figure 36).The highest mean resultant bracing force was observed with Posterior efforts (411.3. N), with the lowest during Inferior (82.8 N) and Anterior (39.6 N) efforts. The overall average bracing force for the gross motor tasks was 210.1 N. Meanwhile for the Precision task, the average bracing force was very low, with an average of 84.6 N. For all exertions, there was little noticeable discrepancy between hand Locations, except for the Superior efforts.

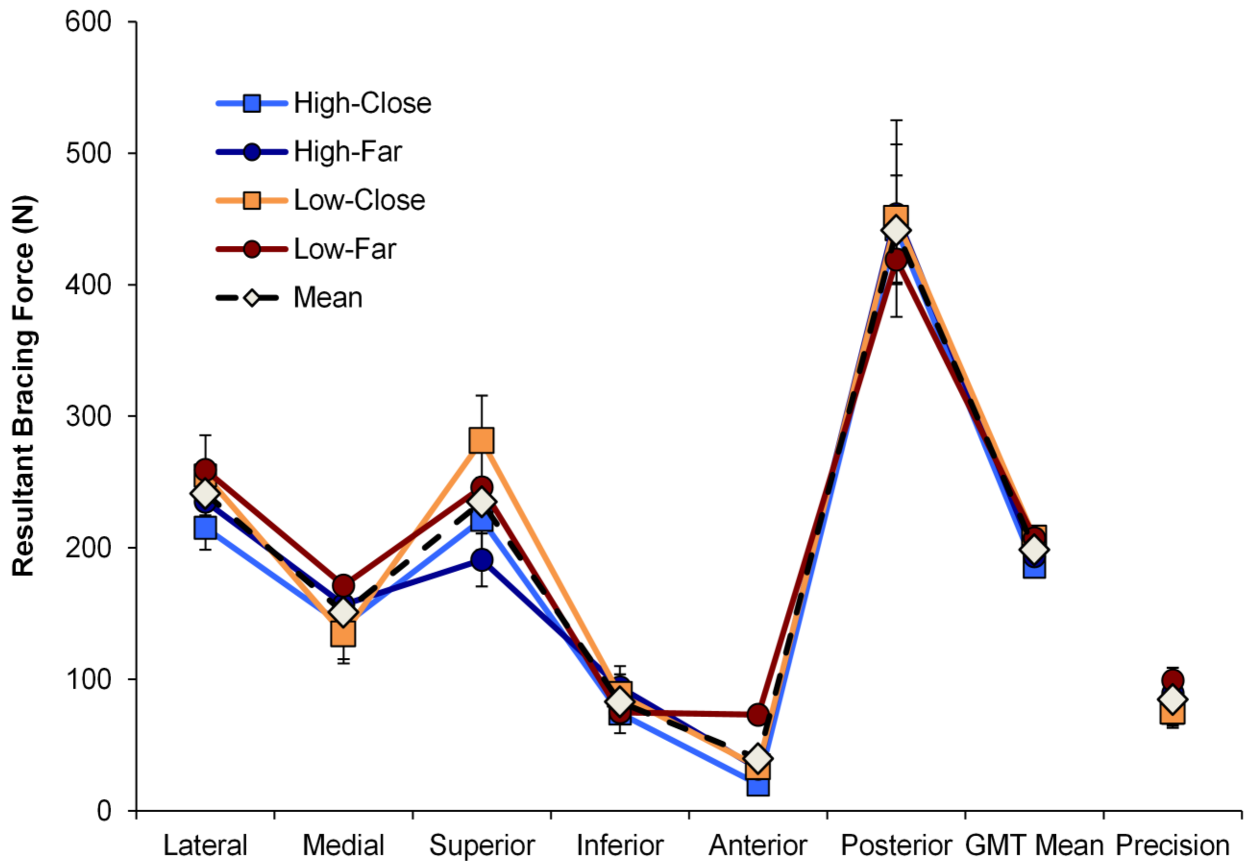


Figure 36: Descriptive statistics showing the average resultant bracing forces for combinations of Location and Direction (n = 18) for trials with bracing present (FSC and OSC trials, n = 346). Standard error bars, are shown. GMT: gross motor task.

Resultant bracing force relative to participant body weight (%BW) and task hand force (%THF) was also analyzed (Figure 37). For the gross motor tasks, Bracing was found to be 32.4%BW for gross motor tasks and 13.4%BW for the Precision task. Relative to the task hand force, the Lateral, Superior, and Posterior efforts all exceeded the task hand force by 168.2%THF, 153.5%THF, and 125.0%THF, respectively, while the Inferior (45.3%THF) and Anterior (18.4%THF) efforts were considerably lower than task hand force.

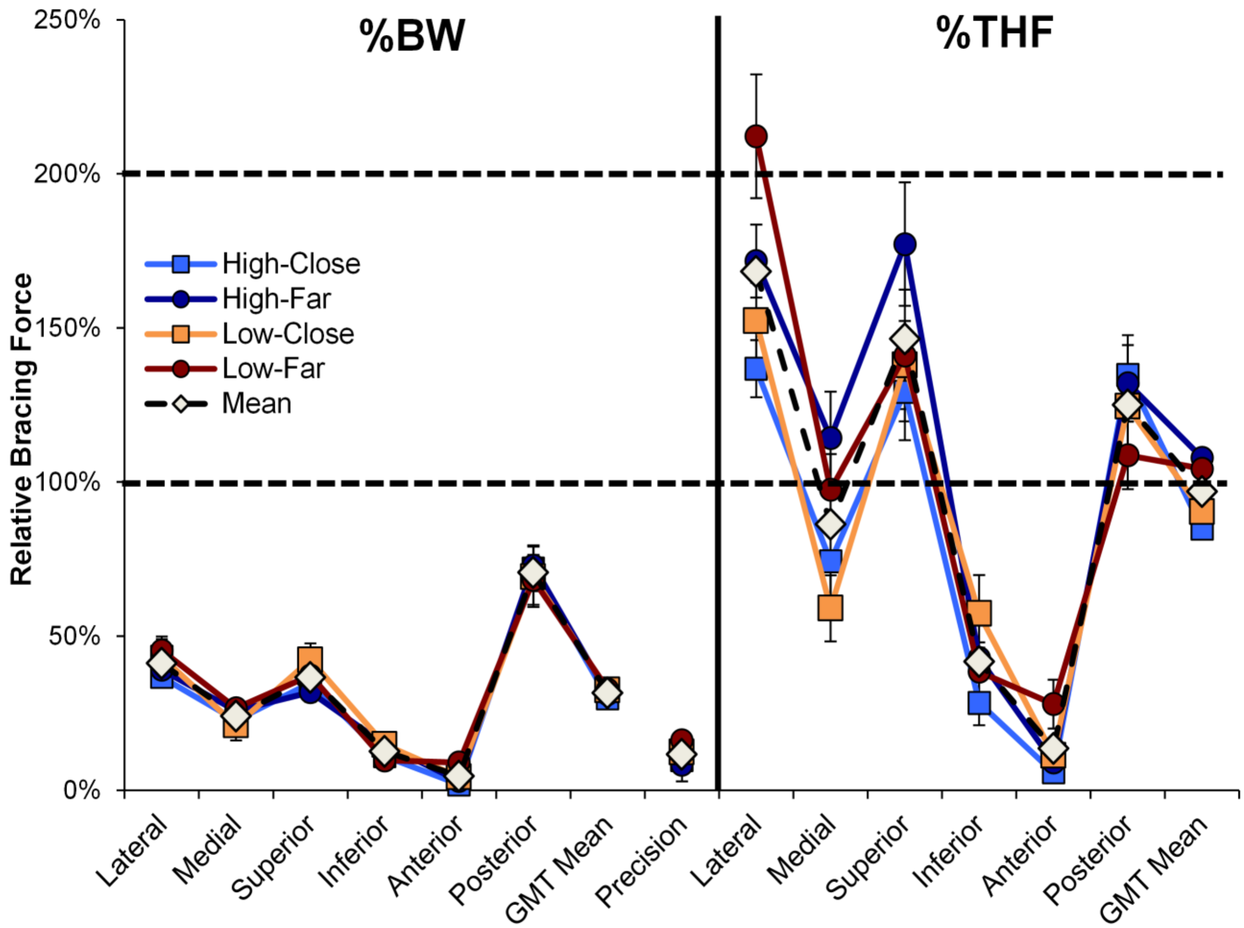


Figure 37: Descriptive statistics showing average relative bracing forces, as a percentage of: left) participant body weight (%BW), and right) task hand force (%THF), for combinations of Location and Direction (n = 18) for trials with bracing present (FSC and OSC trials, n = 346). The %THF for the Precision task is not shown, since the task hand forces were negligible. Mean values for task hand Locations, within hand task Directions, and standard error bars are shown. GMT: gross motor task.

There was also an apparent effect of between Direction and Location on resultant leaning force (Figure 38). The highest leaning forces were associated with the Superior (194.7 N), Medial (179.7 N), and Posterior (166.5 N) exertions. In general, the Low-Far hand Location had the highest forces for most of the Directions. Within the Superior Direction, Low-Far tended to be higher than both High-Close and Low-Close. In general, the leaning forces tended to be lowest for the Inferior and Anterior Directions. The overall average leaning force was 137.2 N for the gross motor tasks, and 53.2 N for the Precision task.

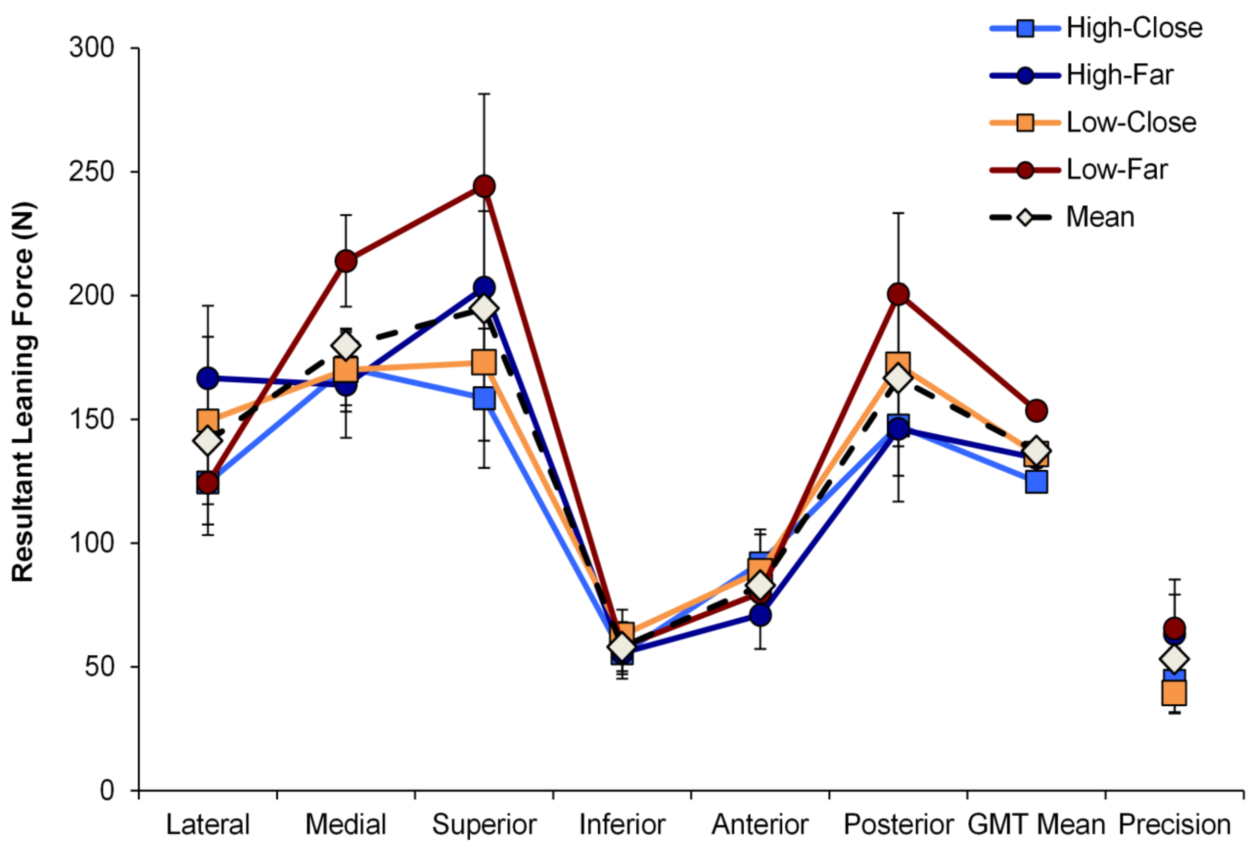


Figure 38: Descriptive statistics showing average leaning forces for combinations of Location and Direction (n = 18), for cases with leaning present (FSC and OSC trials, n = 441). Standard error bars are shown. GMT: gross motor task.

Finally, leaning forces, relative to participant body weight (%BW) and task hand force (%THF), were also analyzed (Figure 39). The average relative leaning forces were 23.3 %BW for gross motor tasks and 9.6 %BW for the Precision task. The average leaning force (as %THF) was much lower than that for bracing, with an average of 80.6 %THF. Leaning forces during Medial and Superior efforts exceeded the task hand force considerably, at 115.8 and 143.3 %THF, respectively, while the Inferior, Anterior, and Posterior efforts were all less than 50 %THF.

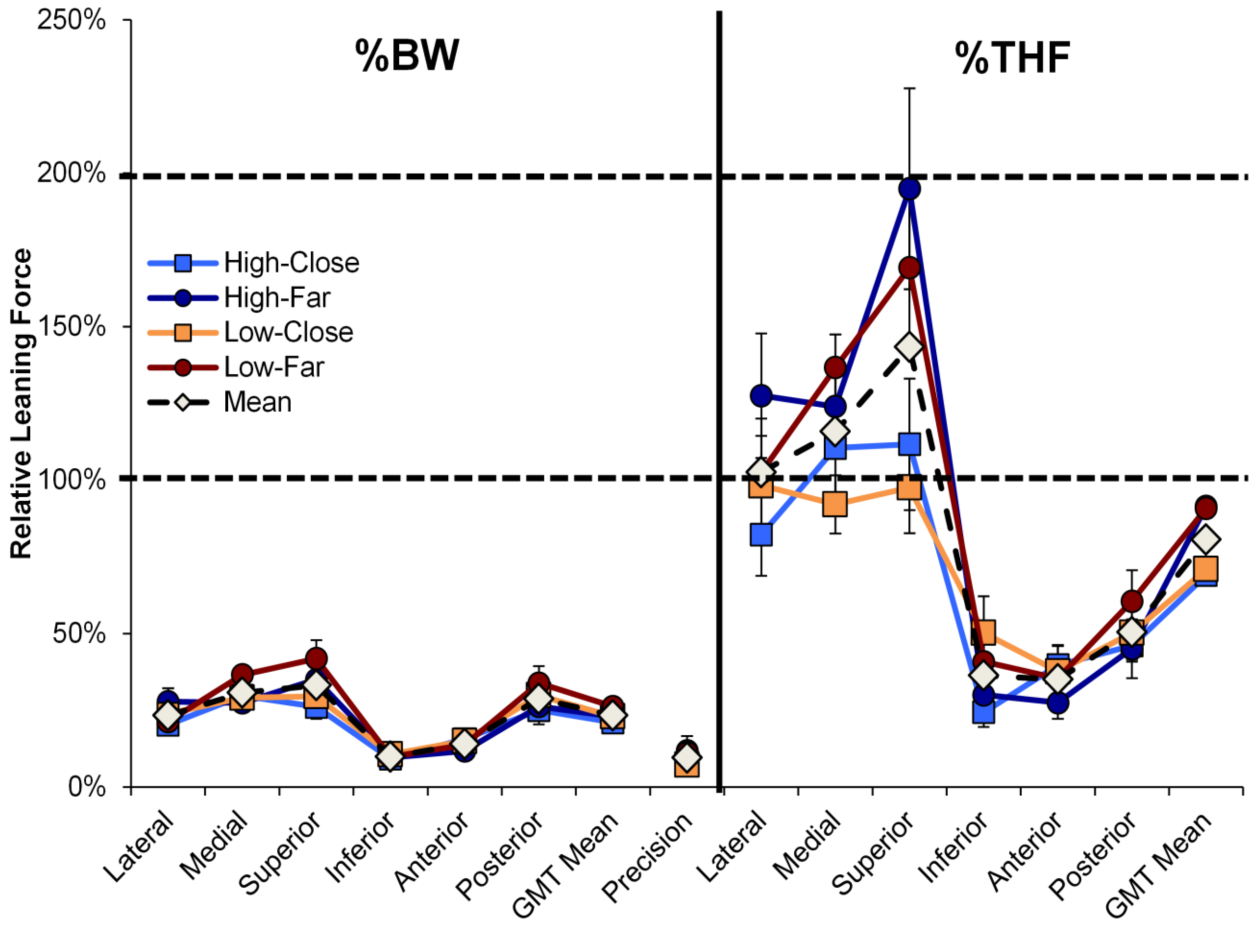


Figure 39: Descriptive statistics showing average relative leaning forces, as a percentage of: left) participant body weight (%BW), and right) task hand force (%THF), for combinations of Location and Direction (n = 18) for cases with leaning present (FSC and OSC trials, n = 441). The %THF for the Precision task is not shown, since the task hand forces were negligible. Mean values for task hand Locations, within hand task Directions, and standard error bars are shown. GMT: gross motor task.

For the gross motor tasks, the direction cosines of the X, Y, and Z force components of the leaning force were analyzed. In general, there was a trend observed with the leaning hand force direction compared to that of the task hand (Figure 40). For all Directions (except for Inferior and Anterior), the highest magnitude leaning hand force components were found to be the opposite direction to the task hand force component. For example, for the Superior effort, the task hand Y force component was -1, while the dominant leaning hand force component was Y at +0.53. In addition, it was interesting to note that the leaning hand Y component remained positive (i.e. contributing an inferior force) within all Directions.

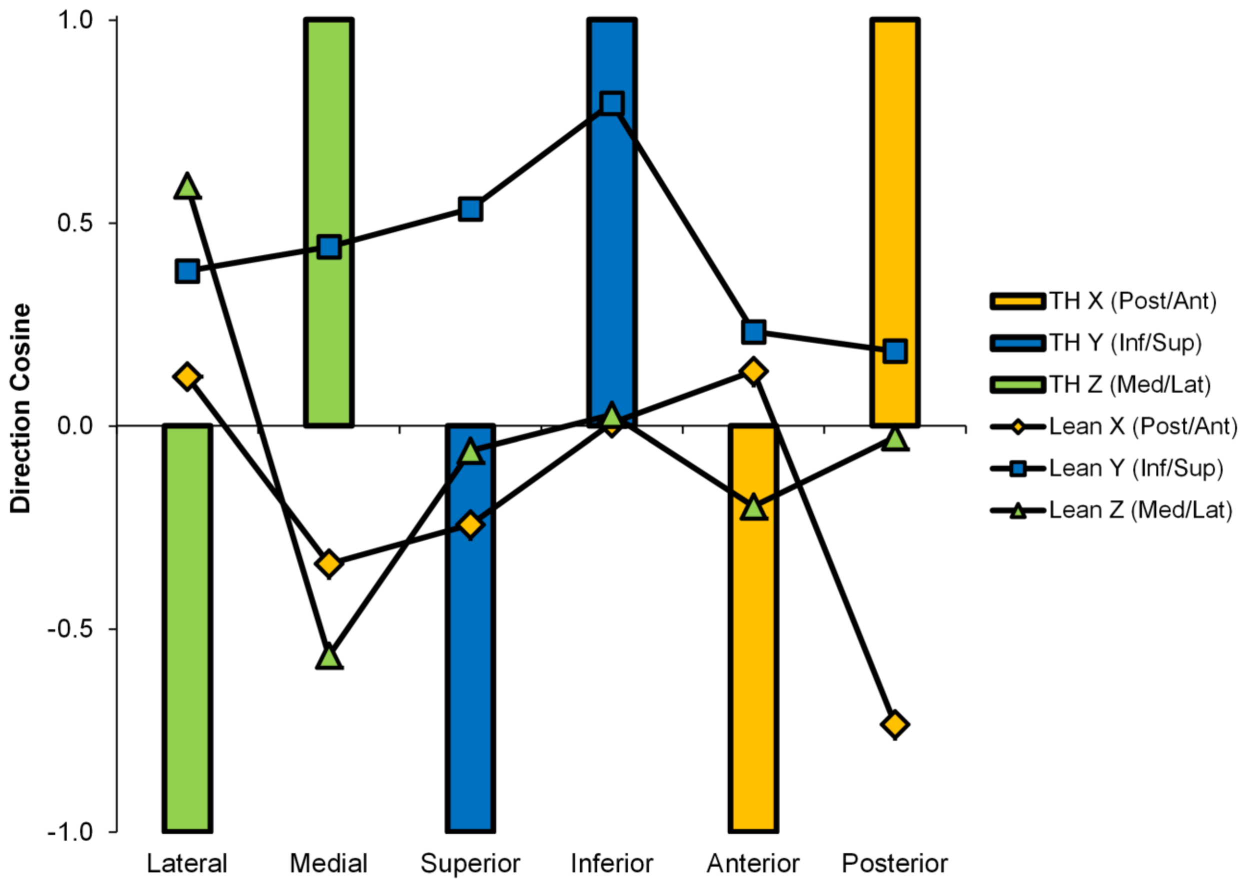


Figure 40: A descriptive comparison of task hand (TH) force and leaning hand force direction cosines in different task hand Directions, for the gross motor tasks. Data are from trials where leaning was present (FSC and OSC trials, n = 441). The bars represent the direction cosine for a given force component within a certain TH exertion (i.e. ±1, 0, and 0), while the lines show the mean values for the leaning hand force components.

4.5 Leaning Arm Joint Loading and Posture

Descriptive statistics were used to compare leaning arm kinetics and kinematics, between task hand locations and tasks, on all cases where leaning was present (n = 441).

Leaning arm elbow moment tended to change based on the combination of Location and Direction (Figure 41). The highest average moments were associated with the Superior (21.0 Nm), Posterior (17.3 Nm) and Lateral (17.0 Nm) efforts. A positive moment value is caused by elbow flexors, while a negative moment is caused by elbow extensors. For the majority of gross motor exertions, Low-Far had the highest moments, while High-Close tended to have the lowest moments for the majority of these exertions. For the Precision task, there was a fairly low mean elbow moment (6.1 Nm), while there was little discrepancy between hand Locations.

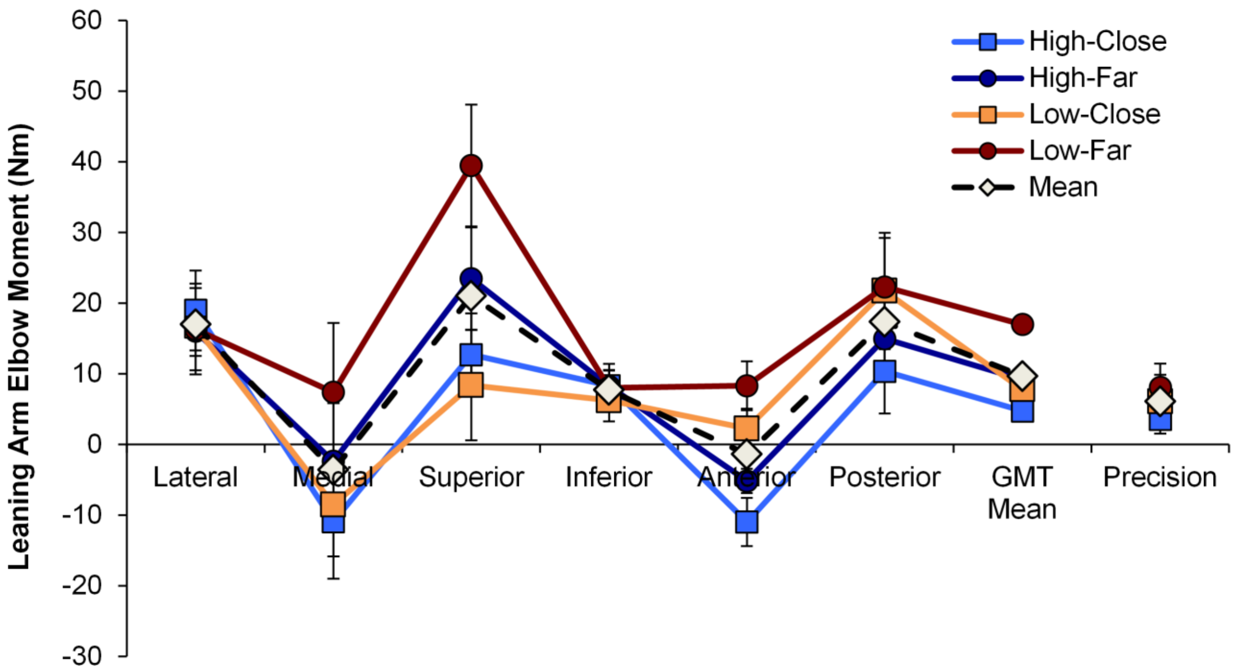


Figure 41: Descriptive statistics showing average leaning arm elbow moment for combinations of Location and Direction (n = 18) for cases with leaning present (FSC and OSC trials, n = 441). Elbow flexors cause positive moments, with extensors causing negative moments. Standard error bars are shown. GMT: gross motor task.

The leaning arm's elbow flexion angle did not change much with exertion (Figure 42). For the gross motor tasks, the angles ranged between 86.4˚ for Superior, to 109.1˚ for the Anterior efforts, for an overall average of 98.3˚ across all gross motor tasks. Within these maximal efforts, the High-Far hand Location tended to have either the lowest angles (Lateral, Medial, Superior and Inferior) or the highest (Anterior and Posterior). Meanwhile, the Precision task had a lower elbow flexion angle compared to all gross motor tasks (73.4˚).

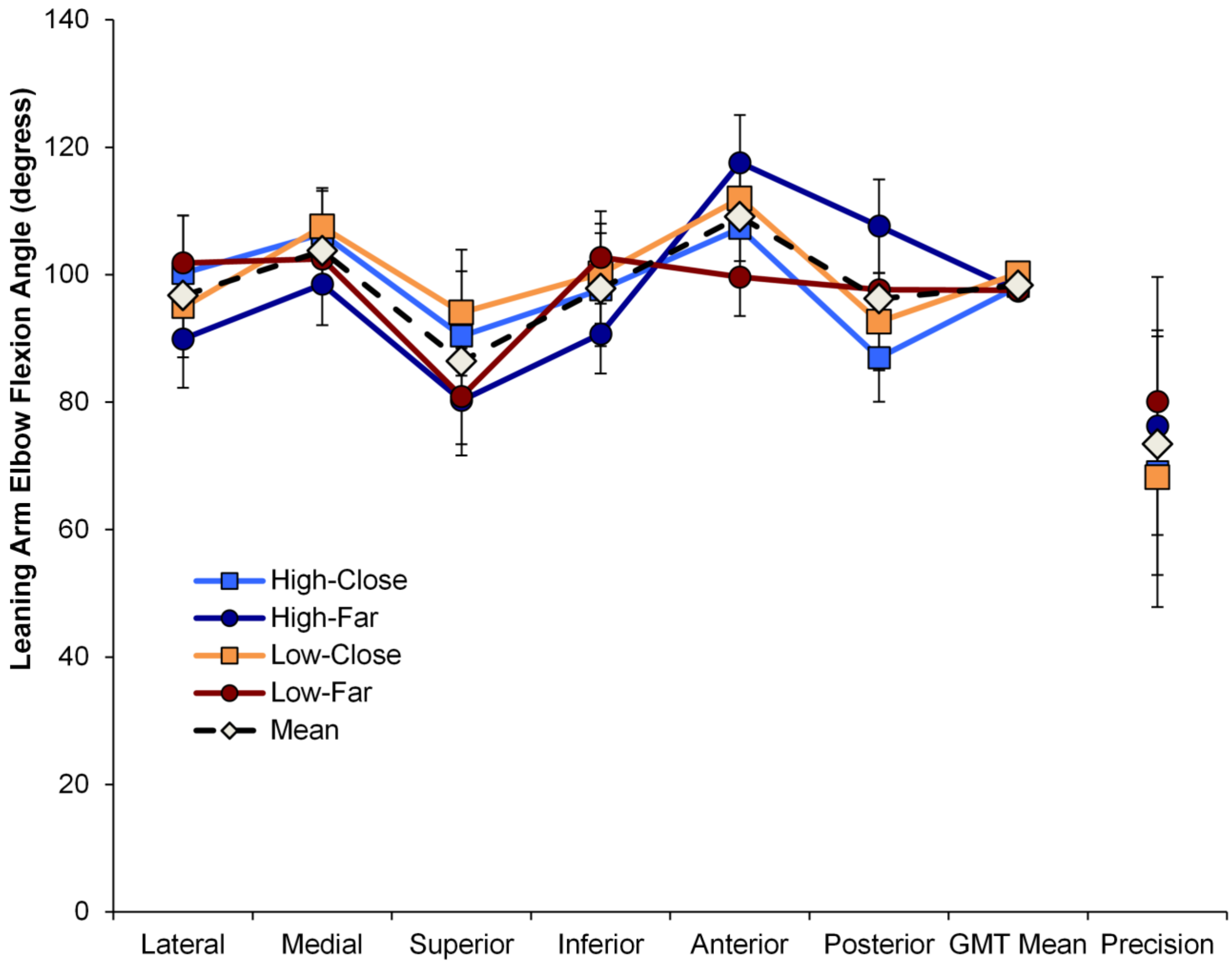


Figure 42: Descriptive statistics showing average leaning arm elbow angle for combinations of Location and Direction (n = 18) for cases with leaning present (FSC and OSC trials, n = 441). Standard error bars, are shown. GMT: gross motor task.

Similar to elbow flexion angle, the leaning arm resultant shoulder angle showed little variance across conditions, ranging from 63.0 Nm for the Medial exertions to 81.9 Nm for the Posterior exertions, for an overall average of 69.5 Nm (Figure 43). Low-Far tended to have the most shoulder rotation across all hand tasks, except for Inferior and Precision. The Precision task hand had comparable shoulder angle values to the gross motor tasks, with an average angle of 72.4˚ across all hand locations.

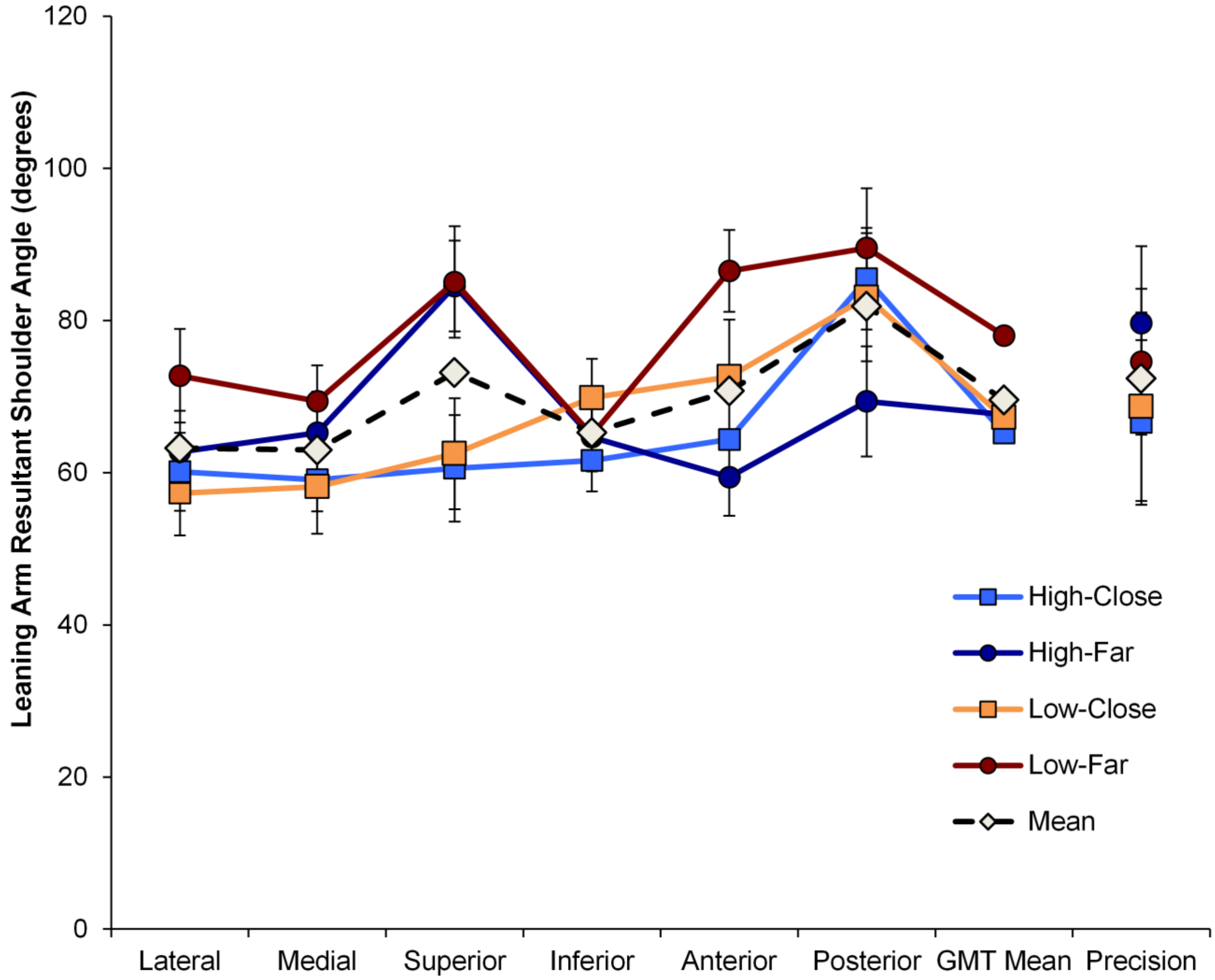


Figure 43: Descriptive statistics showing average leaning arm shoulder angle for combinations of Location and Direction (n = 18) for cases with leaning present (FSC and OSC trials, n = 441). Standard error bars are shown. GMT: gross motor task.

Finally, the leaning arm's resultant shoulder moment was compared across all hand exertions and hand Locations (Figure 44). There appeared to be a large effect of Direction, with Posterior (32.3 Nm) and Superior (30.0 Nm) having the highest average moments. Meanwhile, Inferior (10.2 Nm) and Anterior (16.2 Nm) had the lowest moments of all gross motor tasks, while the Precision task had the lowest moment values of all exertions (7.0 Nm). For more than half of the gross motor tasks, the Low-Far hand Location had the highest values (Medial, Superior, Posterior, and Precision). Conversely, for the same three hand tasks High-Far had the lowest moment values.

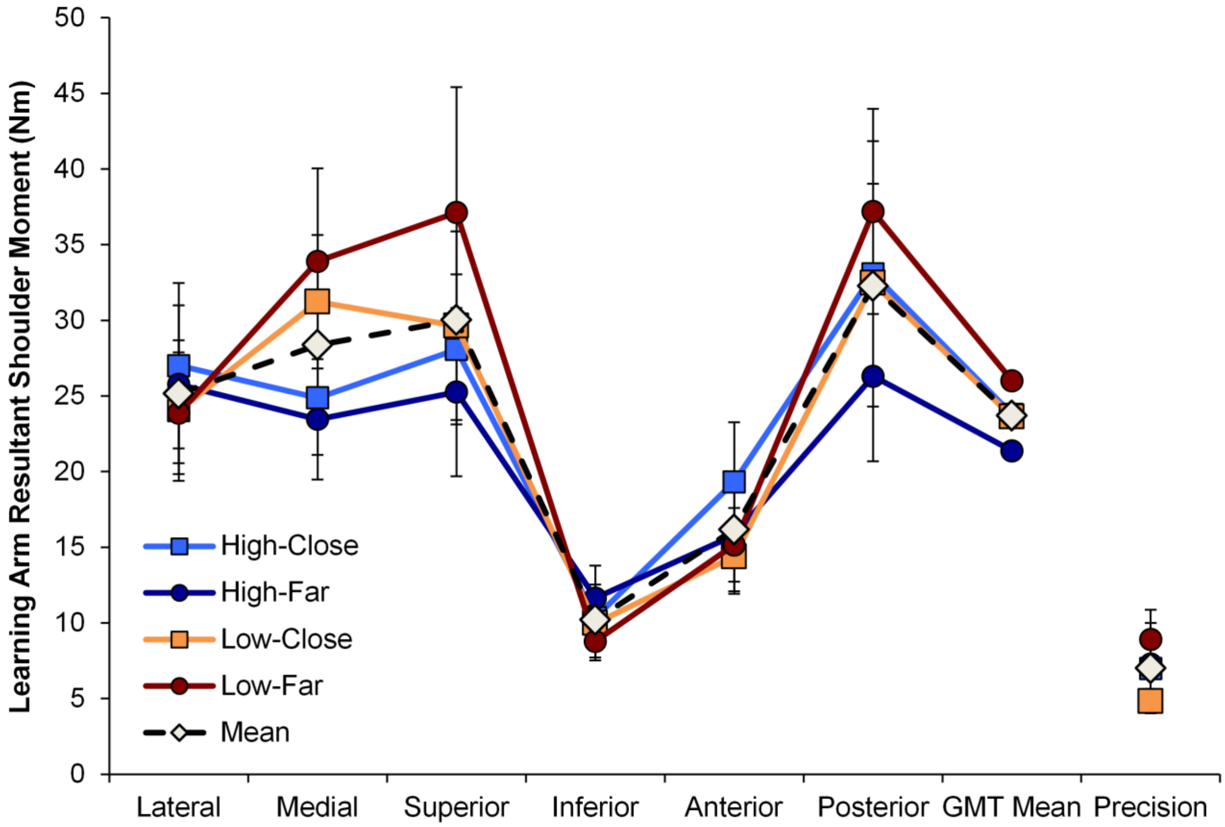


Figure 44: Descriptive statistics showing average leaning arm shoulder moment for combinations of Location and Direction (n = 18) for cases with leaning present (FSC and OSC trials, n = 441). Standard error bars are shown. GMT: gross motor task.

4.6 Fine Motor Precision Task

As stated previously, the primary goal of my thesis was to determine the effects of external support on various outcomes. Therefore, for the fine motor Precision task, only the effects associated with external Support will be presented. Results based on other effects (i.e. Task Hand Location), as well as a summary table for the ANOVA results, can be found in Appendix E.

There was an interaction between Support and Location on task arm elbow flexion angle (Figure 45), with angles being higher with Support, compared to No Support, for all task hand Locations.

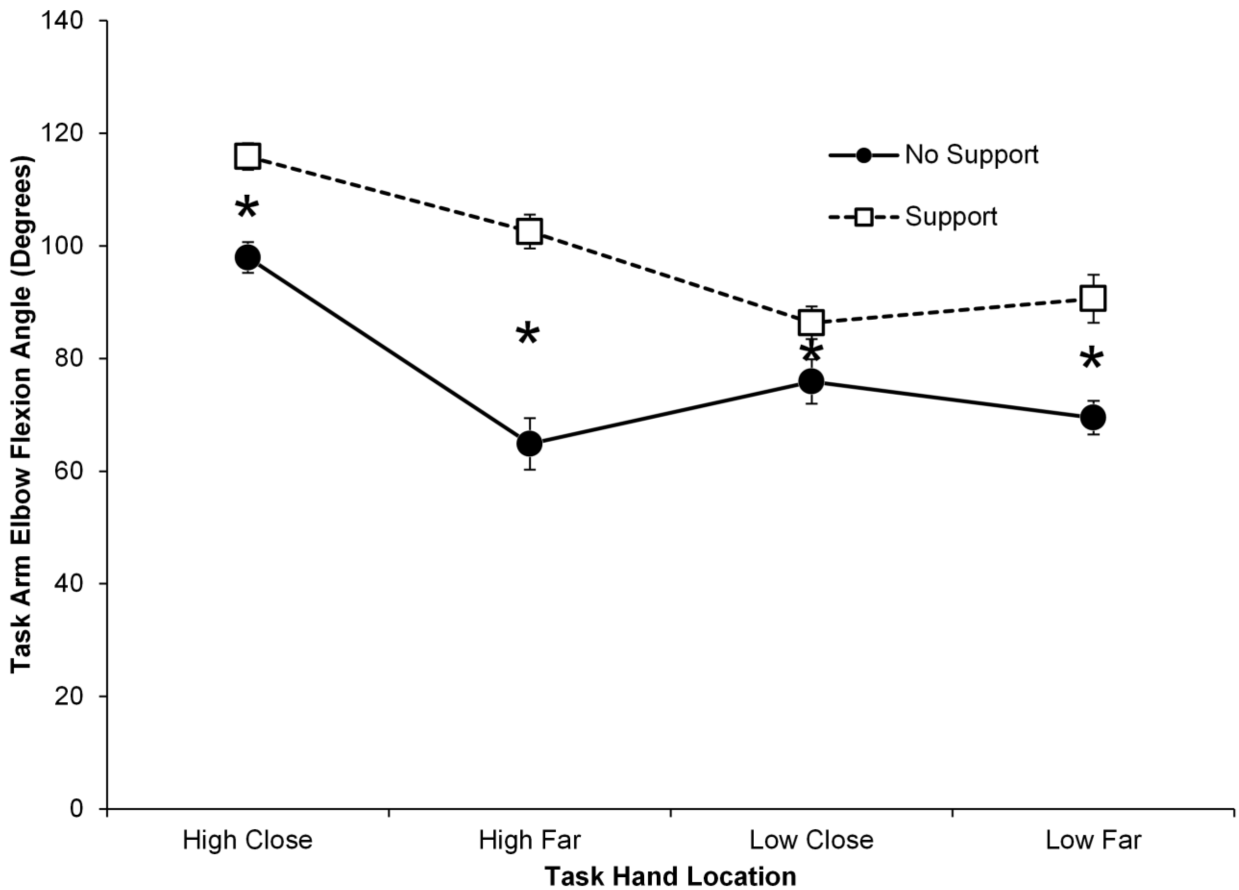


Figure 45: The interaction between Support and Location on task arm elbow flexion angle during the Precision task. Mean values and standard error bars are shown. Significant differences between Supported and No Support are indicated with asterisks ($p < 0.05$).
There was a main effect of Support on the trunk lateral angle for the Precision tasks. Angles were 5.6˚ higher when there was No Support (10.8˚) compared to Support (5.2˚).

There was an interaction between Support and Location for resultant trunk moment (Figure 46), with supported moments being higher at the High-Close Location.

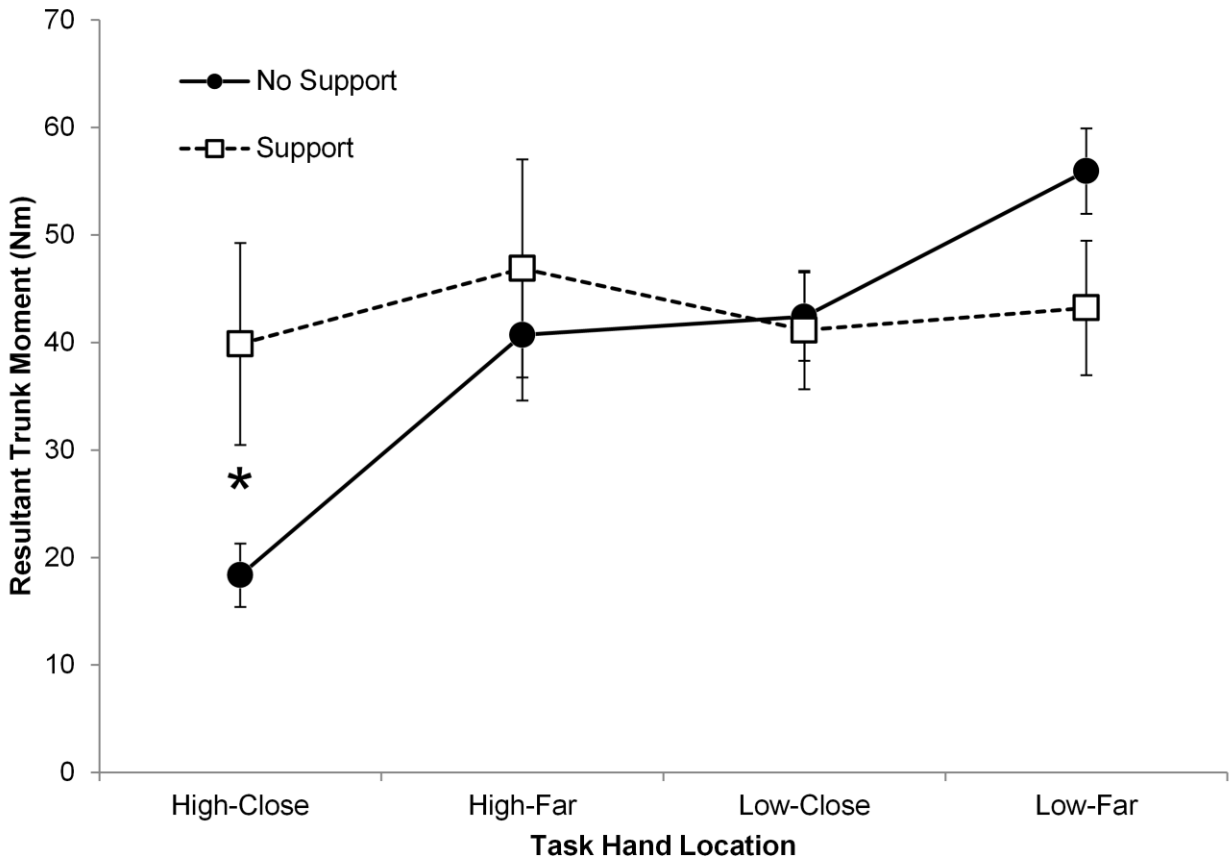


Figure 46: The interaction between Support and Location on resultant trunk moment. Mean values and standard error bars are shown. Significant differences between Supported and No Support are indicated with asterisks (p<0.05).

Finally, while it was hypothesized that external Support would have a positive effect on the performance of the Precision task, there was actually no significant effect of external Support on the task completion time.

5.0 DISCUSSION

The most important findings in this study are listed below. The findings are related back to the hypotheses stated in the Introduction.

1. For maximal effort trials, participants almost always used external support. With Support, they were able to exert an average of 64.8% more force at the task hand, Non-Supported conditions. However, there was no increase in force for the Inferior and Anterior Directions. These findings support my hypothesis, which predicted a positive effect of external support on task hand force, and also support the prediction that there would be no significant increase for the Anterior and Inferior Directions *(section 5.1.3)*.
2. Support appears to have increased task hand force by implementing one, or more, of the following fundamental effects: **a)** generating oppositional forces to the task hand direction, **b)** maintaining balance by counteracting destabilizing moments created by the task hand force, and **c)** getting the task shoulder closer to the task handle to maximize force generating capability of the upper extremity by decreasing the moment arm of the task hand force vector with respect to the joints. My hypothesis was supported by these findings, which correctly predicted the occurrence of effects a) and c) *(section 5.1.1)*.
3. Logistic regression models were created that were able to predict the occurrence of leaning and of bracing quite accurately. Both task demands (task hand force, horizontal/vertical task hand Location, force Direction) and individual characteristics (various joint strengths and anthropometry) were found to be significant predictors of the behaviours. The most interesting, and novel, feature was that a model was created that could accurately predict the simultaneous occurrence of leaning and bracing. The models support my hypothesis that horizontal task hand Location and Direction would be significant predictors. However, it was not true that trunk strength contributes significantly to predicting external support behaviours *(section 5.2.1).*

4. Usage of either the horizontal or the vertical leaning surface depended highly on task demands (Location and Exertion). For a given Exertion, the leaning surface that would be chosen was usually the one that was perpendicular to the line of force exerted at the task hand. In addition, for a given Location, the likelihood of the horizontal surface being used was related to the horizontal distance to the task handle. Finally, the leaning hand Locations, selected on either the vertical or horizontal surface, had a narrow range across the various task conditions *(section 5.4).*
5. Support had little effect on the joint loading of the shoulder and trunk during maximal force tasks. However, there were changes in elbow and trunk angles with Support. This supports a conclusion that there was a trade-off effect in the $M = F \times r$ relationship, where the moment (M) stayed constant (maximal), while there was a decrease in moment arm (r) and an increase in force (F), due to external support. My hypothesis incorrectly predicted that external Support would be associated with decreasing shoulder, trunk, and elbow moments for maximal efforts *(section 5.5).*
6. For the Precision task, external support was used less frequently than with the gross motor tasks. My hypothesis was supported; that support would be more prevalent for Precision tasks with longer horizontal reaches, but incorrectly stated that support would be used in the majority of trials, given that it was only employed in approximately half of the trials. Also, since Support had no effect on the time to completion of the Precision task, I was incorrect in predicting that trials featuring support would be performed faster *(section 5.6)*.

The above findings are essential to the development of external support algorithms within digital human modelling programs, and could some day assist ergonomists when they are proactively predicting worker postural and hand force strategies, with and without external Support. This study featured numerous novel task demands variables that could influence external support behaviours for tasks with known locations (Table 4). In addition, this thesis was the first to show how external Support influences task hand force generation capacity in the intended direction for a given task hand Direction. In comparison, previous research investigating external support either: a) only studied submaximal tasks (Cappelletto, 2013; Fewster, 2013), or b) did not constrain the task hand force direction for maximal efforts (Jones, 2011). This is particularly important for engineers who, while proactively designing parts for manufacturing purposes, want to know how much force a worker can generate in a certain Direction and hand Location, so that part quality/retention can be optimized, while staying within the limits of worker strength.

5.1 External Support and Task Hand Force

5.1.1 Fundamental Effects of External Support on Generating Maximal Task Hand Force

In this study, the primary instruction given to the participants was that they should generate as much task hand force as possible in the intended direction for a given trial. Based on the results, I propose that there were three 'fundamental' effects of external Support that allowed participants to take advantage of external support to maximize task hand force. The application of these effects, in isolation or combination, was observed to be task Direction dependent (Table 7).

5.1.1.1 Effect 1: Oppositional Force Generation

By using external Support, participants were able to apply forces that were oppositional to the task hand force to aid in force generation capability at the task hand. Without external Support, the only reaction forces available, to contribute to the task hand, came from the ground reaction forces and joint stiffnesses (Fewster, 2013). This effect was mainly evident based on the analysis of leaning force directions, which showed that lean hand forces were exerted in the opposite direction of task hand force (Figure 40). Bracing forces were highest for the task hand force directions where oppositional forces with the thighs were easy to create (e.g. posterior, superior). This oppositional force effect is consistent with previous studies, such as Jones (2011), who demonstrated that support increases the ability to produce task hand forces by providing oppositional forces with the leaning hand and/or thighs. She further stated that external support was primarily used to create these oppositional forces, rather than support whole body balance. Furthermore, it has been well documented, in other studies, that force generation capacity is related to the availability of reaction forces (Kroemer & Robinson, 1971; Kroemer, 1974). Depending on the task hand force direction, the added reaction force applied by Support could: compensate for the need for friction at the shoe-floor interface, contribute to the trunk axial twist moment, and/or aid in maintaining balance. For the latter, as noted, contributions to balance can reduce limitations in task hand force generation for certain efforts (Fischer et al., 2013). A visualization of this effect is provided in Figure 47.

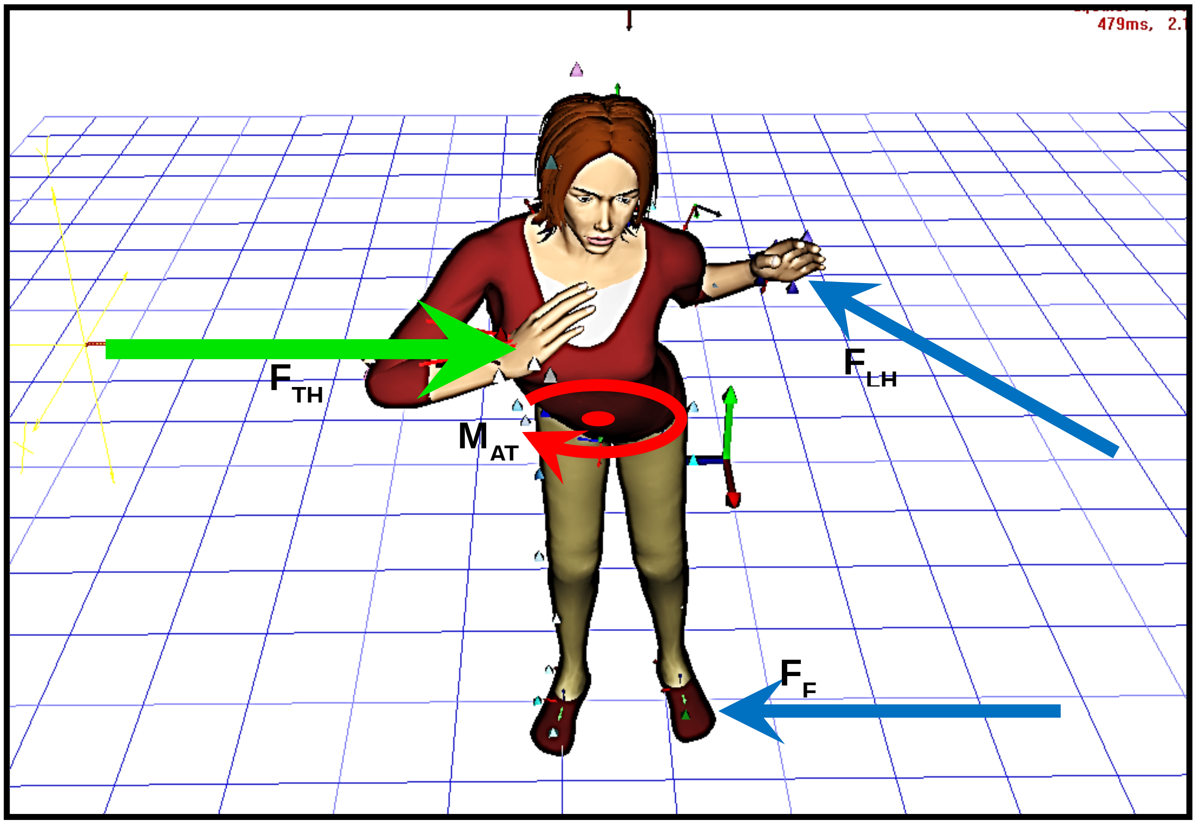


Figure 47: An example of a participant (actual trial) applying a leaning hand force (F_{LH}) to generate oppositional force to the task hand force for a Lateral effort (F_{TH}). The leaning hand force could also act to provide compensation for a torsional moment about the long axis of the trunk (M_{AT}) or friction at the shoe-floor interface (F_F).

5.1.1.2 Effect 2: Getting the Task Shoulder Closer to the Task Handle

By leaning and/or bracing themselves against the apparatus, participants were able to maintain their balance as they shifted their centre of gravity forward to get their task shoulder closer to the task handle. This effect was well documented in previous studies, which has been shown to optimize the force generating capacity of the task arm (Cappelletto, 2013; Fewster, 2013). As the shoulder is moved closer to the handle, there is increased elbow flexion, decreased shoulder rotations and, ultimately, a decrease in the moment arm of the task hand force vector about the shoulder. This decrease in moment arm may increase the amount of force that a joint could produce while maintaining the same maximum moment. In addition, with the shoulder and elbow closer to the middle of their range of motion with increased flexion, the muscles of the upper extremity and shoulder could also be at more optimal lengths for producing force (Murray et al., 2000). Without external Support, participants would need to keep their centre of gravity positioned more posterior, in relation to their base-of-support, to maintain stability. Consequently, the shoulder would now be in a more flexed posture, and the elbow more extended, which are weaker positions for generating force due to the increased moment arm of the task hand force vector and/or increased muscle lengths. In this thesis, elbow angles had increased flexion in almost all supported cases (Figure 32), which indicates that participants were able to get closer to the task handle as a means to increase task hand force. This decrease in the moment arm to the elbow and shoulder, due to support, reduces limitations in task hand force generation for certain efforts (Fischer et al., 2013). Actual examples of this effect are presented in Figure 48.

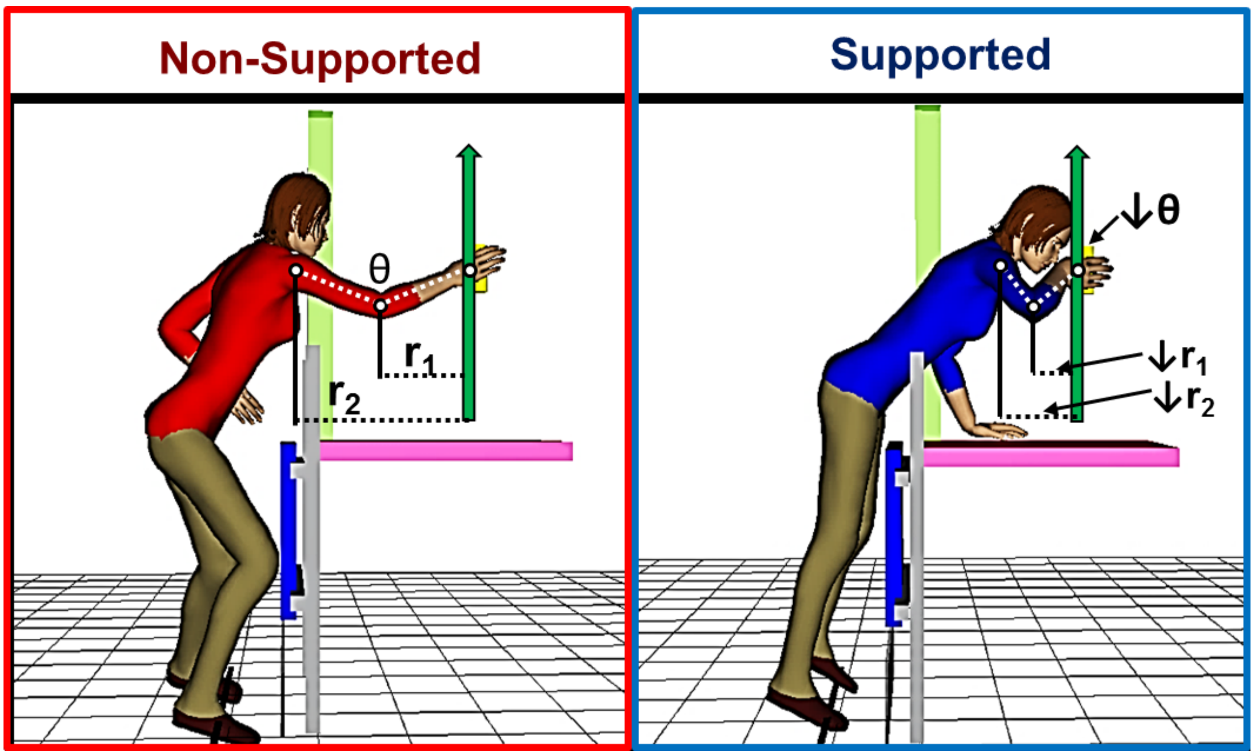


Figure 48: Example of actual postures of a single participant performing a Superior effort in the High-Far hand Location during Non-Supported (red, left) and Supported trials (blue, right). Note, with the Supported trial: 1) there was a decrease in the task hand force moment arm about the elbow (r_1) and shoulder (r_2), and 2) an increase in flexion angle of the elbow (Θ) that was more ideal for applying higher forces (compared to Non-Supported trials).

5.1.1.3 Effect 3: Counteracting Destabilization Forces

The third, and final, fundamental effect of external support is the ability to counteract potentially destabilizing moments created by the task hand (Figure 49). Certain task hand forces, especially when maximal, can put the body out of static equilibrium. For example, when exerting a Superior force with the hand, the reaction force is inferior, and the body is pulled forward and downward due to the moment caused by the task hand reaction force. As Fischer et al. (2013) noted, task hand force generation can be limited by balance (particularly for Posterior efforts). Without external Support, and assuming the participant chose to continue exerting maximally in the intended Superior direction, the participant would most likely lose balance and topple forward. With external Support, the participant could exert a force against the support surfaces that counteracted the forward rotation moment acting about the ankles. For example, an anterior force applied with the thighs against the bracing surface, could be used to maintain stability. Such a use of external support, as a means to maintain balance, is consistent with previous studies (Cappelletto, 2013; Fewster, 2013), and is a means to reduce limitations in task hand force magnitude for efforts that tend to compromise a participant's balance (Fischer et al., 2013).

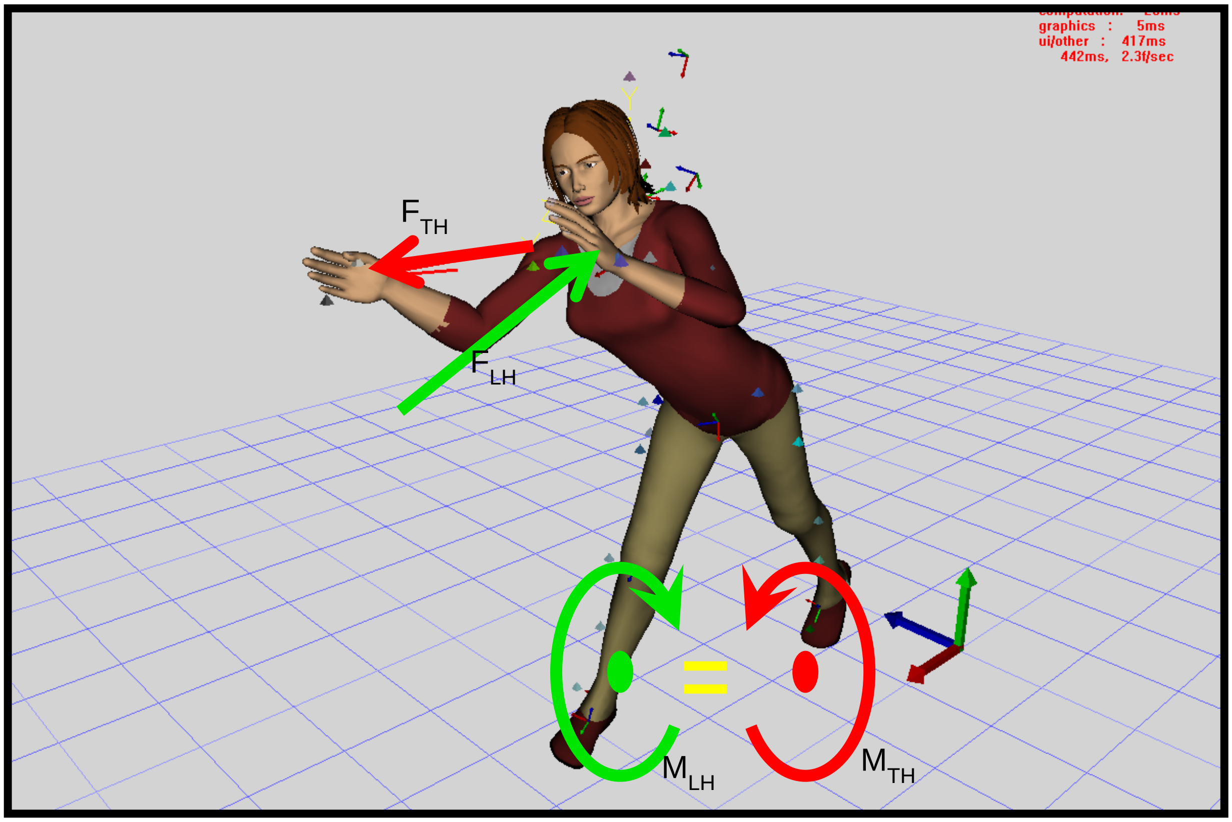


Figure 49: An example of an actual participant performing a Posterior effort (F_{TH}), which caused a destabilizing moment about the base of support (M_{TH}). To maintain balance, the participant applied a force with the leaning hand (F_{LH}) which caused a stabilization moment (M_{LH}) to counteract M_{TH}.

5.1.2 The Accuracy Effect

In addition to those described above, the fundamental effects of external Support combined to provide a fourth effect, which was related more to generating more force in the *intended* direction than the resultant force. I will call this "The Accuracy Effect." This effect seemed to come into play for certain Directions where the line of force was not in line with the shoulder, and/or was destabilizing (e.g. Medial, Lateral, Superior). With Support, participants were able to use the apparatus as a stabilizer while getting the task shoulder closer to the task handle. In this stable position, participants could apply a high absolute force with a resultant vector that was 90% in the intended direction (required threshold for a successful trial), without risking a loss of balance. Based on anecdotal evidence, for trials without Support, participants found it quite difficult to exert a certain task hand force that was of maximal effort while still achieving the 90%

threshold criteria. For the Superior direction, this was likely due to the destabilizing forces that would pull the participant forward. In lieu of Support, the participants would naturally alter the task hand force to counter this moment by applying a more *anterior* force and, thus, often fail to reach the required 90% threshold. Even for the Medial and Lateral Directions, participants naturally brought their centre of gravity forward (into a more unstable position) to generate more force. However, this would still result in exerting a more anterior force on handle to maintain balance and, thus, fail to meet the directional criteria. To solve this issue, participants would stand with their centre of gravity more posterior, with an extended arm (Figure 48), to maximize their stability and minimize their need for these compensational forces on the task handle. However, these postures were not ideal for generating high absolute task hand forces, even if they were still, presumably, maximal for that condition. This could explain the large relative difference in task hand forces observed for the Medial, Lateral, and Superior tasks (see section 5.1.3.1).

5.1.3 Changes in Task Hand Force with External Support

On average, participants were able to generate 64.8% more force in the intended direction with the task hand, when using Support (Figure 31). There was a significant increase in maximum force for all Directions except for Anterior and Inferior. In comparison, Jones et al. (2013) reported an average increase of 40.4% during the maximal hand force tasks when external Support was used. However, her task hand force comparisons were between resultant forces, which were not controlled for direction (i.e. forced to be mostly in the intended direction). As explained above, the Accuracy Effect could have accounted for her lower discrepancy in forces, between Supported and Non-Supported conditions.

5.1.3.1 Medial, Lateral, and Superior Directions

Testing and analyzing maximal Medial efforts was a novel aspect of my study (Table 4). Of all the Directions, the Medial efforts had the largest relative increase (119.7%) in task hand force when Support was used (Figure 31). This large discrepancy, between Support conditions, is likely due to three factors.

1. First, the Medial Direction was subject to the Accuracy Effect, as explained previously (see section 5.1.2). The Non-Supported trials were very low in force, since it was very difficult to shift the body forward to generate high, maximal task hand forces without destabilizing the body.
2. Oppositional forces were very easy to generate during Medial efforts, given the vertical leaning post that was provided in the setup. Participants often would exert a very strong leaning force in the oppositional (lateral) direction against this post (Figure 40). On average, these resultant leaning forces were even higher than the task hand force (115.8 %THP) (Figure 39).
3. For the Medial efforts, the participants were effective in getting the shoulder closer to the task handle. This was evident by the large, consistent increases in elbow flexion angle across all task hand locations with external Support (Figure 32), and the considerable resultant bracing force (151.8 N) (Figure 36). Both findings indicate that the participants likely maximized their forward positioning to get the task shoulder close to the task handle for increasing task hand force.

A similar, but less pronounced, trend was observed for both the Lateral (85.9% increase) and Superior (91.3% increase) efforts (Figure 31). Both Directions were prone to the Accuracy Effect since, due to instability, the 90% directional requirement was difficult to achieve for both during the Non-Supported trials. As a result, the Non-Supported conditions had relatively low task hand force values, resulting in a large relative increase once support was introduced. In addition, the resultant leaning forces showed high oppositional components for both Directions (Figure 40).

For Superior efforts, there was likely a further contribution from the high resultant bracing forces (234.9 N) (Figure 38), which were presumed to be, at least partially, oppositional to the task hand force. Finally, compared to Medial efforts, both the Lateral and Superior efforts had similar elbow flexion increases associated with external Support (Figure 32), which indicates that the participants were getting closer to the task handle, to exert high absolute forces during the Supported trials.

In comparison, Jones et al. (2013) reported a 60% increase in task hand force for the Superior efforts with external Support, which was approximately 30% less than observed in the present study. This was likely due to the fact that Jones et al. did not control for task hand force direction, such that her outcomes were not affected by the Accuracy Effect. Thus, her Non-Supported trials would have had a higher resultant force, due to the lack of directional control, accounting, at least in part, for her lower observed discrepancy between Supported vs Non-Supported for Superior efforts.

5.1.3.2 Posterior Direction

Support resulted in an 84.6% increase in task hand force for the Posterior Direction (Figure 31). Interestingly, the Posterior Direction had the highest absolute task hand force when Supported (325.8 N), likely due to the possibility that both leaning and bracing support surfaces could be used to apply anterior support forces, directly opposite to the task hand (Figure 19). The Posterior effort’s absolute resultant bracing forces were by far the highest (441.3 N) (Figure 36), in addition to high resultant leaning forces (166.5 N) (Figure 36) that were also directionally oppositional to the task hand force (Figure 40). In comparison, Jones et al. (2013) reported only an average increase of 44% in posterior task hand force with Support. This finding was likely due to the fact that her setup did not include the vertical leaning post available in my study (Figure 9). In short, the task hand force for the Posterior Direction was mostly affected by the oppositional forces generated by Support.

5.1.3.3 Anterior and Inferior Directions

For the Anterior Direction, task hand force was virtually equivalent between Supported and Non-Supported conditions. The first explanation is that, for this task, it was clear that any leaning being employed was not used to create oppositional forces. Rather, a mostly anterior-inferior leaning force vector was employed by the participants (Figure 40). Resultant leaning and bracing forces were also quite low, compared to other Directions (14.0 and 4.5 %BW, respectively) (Figure 39 & Figure 37). In comparison, Jones et al. (2013) found a 14% increase in task hand force with external Support, which was higher than the 2.7% increase reported here. This is likely explained by the horizontally oriented bar, that ran transversely to the participant in her setup (Figure 9). That surface could have allowed participants to more easily exert oppositional forces to the anterior task hand force vector. This type of feature was not present in my apparatus, which included only a flat horizontal surface (Figure 19). Thus, oppositional forces were not easily created by the leaning arm. Another explanation might relate to the elbow flexion angles, which did not change for Anterior efforts (except for the High-Far location). This showed that, instead of flexing the elbow and getting closer to the task handle, for most cases participants used a "straight-arm" technique, where they would lean into the arm, which transferred force generated from the from ground reaction forces, legs, and trunk, to generate task hand force, rather than from the elbow and shoulder joints. Hence, there was no difference between Supported and Non-Supported conditions task hand forces for Anterior Direction.

The testing and analysis of maximal Inferior efforts was another novel aspect of my study (Table 4). For the Inferior Direction, there was a trend (but not significant) for a 32.6% increase in task hand force with external Support. There were many similarities to the Anterior Direction, in terms of leaning and bracing characteristics. Similar to Anterior efforts, relative resultant bracing and leaning forces were also quite low (12.6 and 9.8 %BW, respectively) (Figure 37 & Figure 39). Meanwhile, leaning hand forces were unidirectional to the task hand force (Figure 40). However, the increased elbow flexion angle for Inferior efforts showed that participants were still getting their task shoulder closer to the task handle (Figure 32), which is likely the sole effect responsible for the relatively small increase in task hand force with Support. Fischer et al. (2013) found that Inferior task hand forces are mostly limited by joint strength, which supports this explanation.

The above findings provide evidence that leaning and bracing was not generally used to generate oppositional forces to the task hand for Anterior and Inferior efforts. Based on the flat surfaces provided in my setup, oppositional forces would have been very difficult to generate by either the leaning arm or thighs. These findings lead me to conclude that external Support was least beneficial, when exerting task hand forces in the Anterior and Inferior Directions. This conclusion is consistent with previous studies (Fewster, 2013; Jones et al., 2013). It is interesting to note that these behaviours were still quite prevalent for both the Anterior and Inferior exertions (greater than 93% occurrence), so I propose that it is more likely that external support was primarily employed for: 1) bringing the body/task shoulder closer to the task handle (for Inferior efforts only), and/or 2) “pushing-off” the support apparatus to return the body to upright position from the forward position after completion of the task (for both Inferior and Anterior efforts). For the latter effect, I can attest that there were many instances where the bracing and leaning forces were highest after the task hand exertion was completed, although it was not analyzed for this thesis. Further analysis could reveal that, for these exertions, external support strategies are employed due to cognitive planning for an eventual “push-off”, rather than to generate oppositional forces during the task hand exertions.

Table 7: A summary of all the significant effects of external Support on task hand force generation as explained in Section 5.1.1 and 5.1.2. Each check mark indicates the relevance of a given effect for a task hand effort Direction, based on the results of this study. Directions shaded in green had significant increases in force with Support, while those in red had no significant effect of Support.

Effect	**Lateral**	**Medial**	**Superior**	**Inferior**	**Anterior**	**Posterior**
Generating Oppositional Forces	✓	✓	✓			✓
Getting Task Shoulder Closer to Task Element	✓	✓	✓	✓		✓
Counteracting Destabilizing Task Hand Moments	✓	✓	✓			✓

5.2 Prediction and Changes in External Support Behaviours

5.2.1 Prediction of External Support Behaviours

Three logistic regression models were created that correctly predict leaning, bracing, or simultaneous leaning and bracing 86.3%, 79.8%, and 74.2% of the time, and explained 34.0%, 30.4%, and 24.3% of the variance, respectively. These values are very comparable to previous studies (Table 8). Based on the significant predictors in the models, I concluded that the likelihood of choosing one of the three support strategies was dependent on both task demands and individual strength and anthropometric characteristics.

Table 8: A summary of the regression model characteristics developed from the previous three external support studies (left) in comparison to the models from this thesis (right, shaded in green). TH: task hand.

	Cappelletto (2013)	**Fewster (2013)**	**Jones (2011)**	**Liebregts (2014)**
Behaviour	Bracing	Leaning	Force generation strategy (x5)	**Leaning, Bracing, Leaning & Bracing**
% Correct	80%	92%	65-88%	**74.2-86.3%**
R^2	0.35	0.70	N/A	**0.24-0.34**
Significant Task Variables	- TH force direction - TH vertical location - TH horizontal location	- TH force direction - TH horizontal location	- TH force direction - TH horizontal location - TH force magnitude - Surface availability	**- TH force direction** **- TH horizontal location** **- TH force magnitude**
Significant Personal Variables	- various joint strengths	- various joint strengths	- Stature - BMI	**- various joint strengths** **- stature, body mass, anthropometry**

5.2.2 Changes in External Support Behaviours

In general, there was little variability in the data, with regards to whether or not participants used support. As was apparent in the results, external support was utilized 93.0-100.0% of the time for the maximal hand force trials. This comes as no surprise, since their objective for the majority of conditions was to exert as much force as possible at the task hand, so taking advantage of the fundamental effects of Support was a priority.

However, there were some other interesting trends observed. First, there was a notable decrease in the frequency of bracing for Anterior efforts, where oppositional forces were very difficult to generate (Figure 28). Based on the lack of change in elbow flexion angle for these tasks (Figure 32), it is clear that many participants chose to stand further back, extend their arm, and use a straight-arm strategy to generate force primarily by leaning forward into the task hand. In these cases, the only external support available to the participant would be the use of a leaning hand, since, with the straightened arm, the body would be further away from the bracing surface.

Also, for bracing behaviours, the ‘Far’ reach Locations had the highest frequency of bracing across the majority of exertions (Figure 28). This was consistent with findings of Cappelletto (2013), who reported that bracing was employed in 94% of the Far conditions compared to only 42% of the Close conditions. The most likely reason for this increase in bracing behaviours is to improve balance. As previously discussed, for almost all Directions (except for Anterior), participants aimed to get as close as possible to the task handle to generate task hand force. With farther reaches, bracing could be more beneficial for maintaining balance due to the greater moment arm that the task hand force would have about the participant’s base of support. However, one anomaly is that, for some Directions, like Medial and Lateral, there was no increase in destabilizing moment with increased horizontal reach. Thus, it cannot be ruled out that the increase in bracing was simply a consequence of participants getting as close as possible to the task handle, which required consequential contact (and force generation) against the bracing surface.

5.3 External Support Kinetics

5.3.1 Resultant Leaning Force Magnitude and Direction

There were a few trends observed with the leaning forces from the results of this study. First, the leaning forces were primarily utilized to oppose the task hand force for all Directions, except for Inferior and Anterior (Figure 40). Interestingly, leaning forces, that had large oppositional components, also tended to have the highest absolute resultant leaning force, particularly for Superior (consistent with Fewster, 2013), Medial and Posterior (Figure 38). Since there was a large contribution of oppositional forces to increase the task hand force for these Directions, then it was expected that the task hand force, in turn, would aid further increase the force going in to the leaning surface. This was an expected trend based on the findings from Jones (2011), who reported that task hand force was actually a significant predictor of leaning hand force.

For the gross motor tasks with leaning, the average relative leaning force was 23.3 %BW (Figure 39). In comparison to previous studies that reported relative lean force, this value was very high. Fewster (2013) reported average leaning forces ranging from between 3.6-8.9 %BW. Since she was exclusively testing submaximal task hand loads, with two of her three exertions being Inferior and Anterior, it was expected that her average leaning hand forces would be lower. In addition, Fewster’s setup lacked a centred, horizontal leaning surface, which appeared to have provided participants with a more inviting, comfortable surface to place more body weight (Figure 8).

Meanwhile, much lower leaning forces were observed with the Precision task (average = 9.6 %BW across all task hand Locations) (Figure 39). This was comparable to Lardi & Frazer (2003), who reported relative leaning forces of 10-15 %BW while participants performing precision tasks, which also involved hand-starting a nut to a bolt. Godin et al. (2008) reported relative leaning hand forces of 5.5-12.1 %BW while performing a series of simulated automotive assembly tasks (e.g. hose insertion, etc.). Although they did not report task hand force, it was assumed that many of their task elements involved some level of precision (e.g. hose insertion, etc.). Overall, the comparison between these previous studies, and the findings of this thesis with respect to fine motor tasks, support Jones's (2011) assertion that leaning hand force can be predicted by task hand force, since the low force associated with the Precision task resulted in low leaning force (Figure 50).

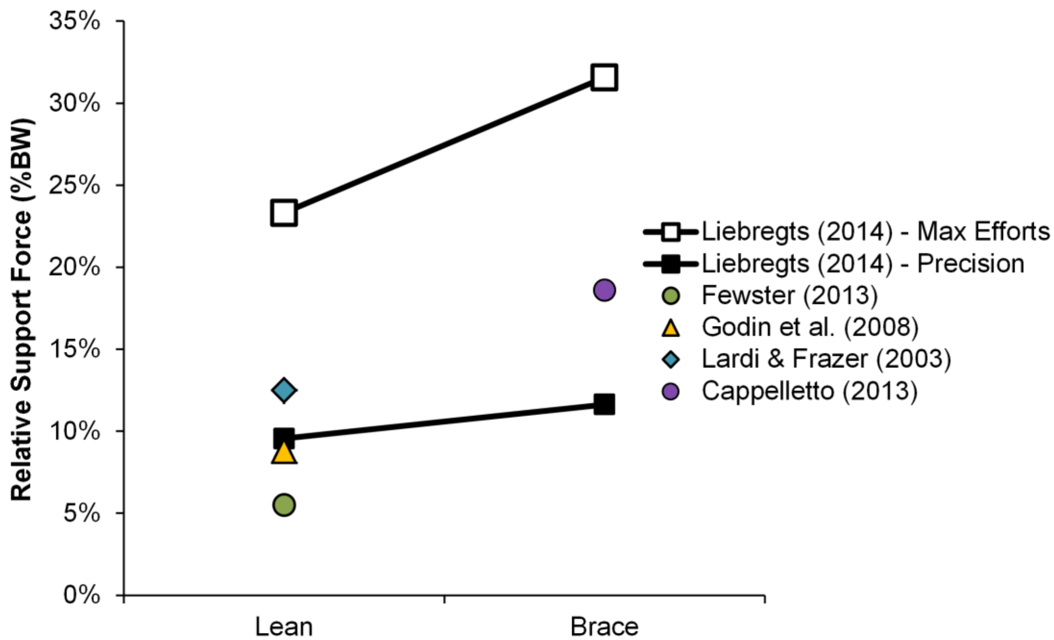


Figure 50: The mean relative leaning and bracing forces reported in this thesis for the maximal and Precision tasks (square plots), compared to the approximate forces from previous studies, which tested submaximal hand tasks (Cappelletto, 2013; Fewster, 2013), precision hand tasks (Lardi & Frazer, 2003), or elements of both (Godin et al., 2008), are also shown.

The Low-Far Location often resulted in the highest leaning forces across almost all Directions compared to the other Locations, including the Precision task (Figure 38). With an increase in reach, participants shifted their bodies forward to get closer to the task handle, which would require more leaning force. This increase in forward body displacement of the centre of mass, would result in a greater destabilization moment caused by the body about the base of support. In addition, for more destabilizing effort Directions (i.e. Superior, Posterior), the task hand force would have a greater moment arm about the base of support at farther reaches, which would subsequently increase the leaning force required to maintain balance.

5.3.2 Resultant Bracing Force Magnitude

For resultant bracing force magnitude, there was an obvious effect of task hand effort Direction. For the gross motor tasks with bracing, the average resultant bracing force was 198.4 N, or 31.6 %BW (Figure 36 & Figure 37). Specifically, the highest forces were associated with the Posterior, Lateral, and Superior Directions, while the lowest were associated with Anterior, Precision and Inferior efforts. This was consistent with previous studies, which reported an increase in bracing force with Superior and Posterior efforts, and a decrease in bracing force with Inferior efforts (Cappelletto, 2013; Jones, 2011). One contrasting finding, however, is that Cappelletto (2013) reported an average bracing force of 117 N for the Superior and Posterior Directions, while this thesis reports much higher means of 234.9 N and 441.3 N, respectively. Since this study required maximal task hand forces, it is possible that, similar to leaning force, task hand force is a predictor of bracing force magnitude.

It was expected that bracing force would increase with task hand forces in the Posterior and Superior Directions, due to the destabilizing effects of both force vectors, which would require increased counteracting forces for stability. However, another novel finding my thesis was that high resultant bracing forces were also found with Medial and Lateral efforts. This is interesting since neither Direction results in a fore-aft destabilization moment acting about the base of support. Furthermore, oppositional forces to the Medial/Lateral exertions were difficult to create with the thighs against the bracing surface. It is possible, then, that the high bracing forces were a consequence of the participants getting as close as possible to the task handle to generate the maximal task hand forces.

5.4 Leaning Hand Placement and Position

For trials where leaning was observed, the overall frequency of horizontal and vertical surface use was 46.3% and 53.7%, respectively (Figure 30 a). The horizontal surface was predominantly used during the Superior, Inferior, and Precision efforts, while the vertical surface was more prevalent for efforts in the Medial, Anterior, and Posterior Directions. In general, participants chose to use surfaces that were perpendicular to the task hand force. As noted previously, the use of these perpendicular surfaces increases the oppositional component of the external support force vectors, which increases the ability to exert task hand force. The one anomaly was the Lateral Direction, which had a relatively even distribution of use of both surfaces. This was likely due to the fact that it was rather uncomfortable to exert a Lateral force, with the left hand, against the vertical leaning post, which would likely maximize shoulder external rotation demand. It is possible that participants preferred the horizontal surface for comfort purposes, and depended on friction against the flat surface to exert oppositional forces with the leaning hand.

It was also interesting that the task hand horizontal Location increased the use of the horizontal surface, as it was used in 45% and 66% of cases for High-Far and Low-Far, compared to 31% and 41% for High-Far and Low-Far, respectively (Figure 30 b). With the increase in horizontal reach, participants had to rotate their bodies further forward to reach the task handle. It is likely, in these cases, that they chose the horizontal surface since it allowed them to apply a downward lean force into the horizontal surface with less moment on the elbow and shoulder, compared to if they leaned against the posterior-laterally positioned vertical surface.

The vertical hand position did not vary greatly between combinations of task hand Location and Direction, ranging between 66.8-71.2% of stature when pooled within Direction, and 66.6-72.7% of stature when pooled within Location (Figure 30). This was very similar to Fewster (2013), who reported little change between leaning hand vertical positions (65-71% of stature).

To the best of my knowledge, my thesis was the first to study leaning hand placement along a large, horizontal leaning surface. Interestingly, similar to the vertical hand placement, the horizontal hand position had little variance between task hand exertions Locations. The average horizontal hand placement was 26.6% of stature anterior to the origin line, while ranging between 23.8-29.9% of stature when pooled within Locations, and 23.1-29.0% of stature when pooled within Directions. This finding supports Fewster's (2013) conclusion that participants may have a very narrow range when it comes to comfortably positioning the leaning hand.

5.5 Task Arm and Trunk Loading

The majority of external support studies have reported that using external Support can reduce the moment at critical joints, including the shoulder (Cappelletto, 2013; Fewster, 2013) and low back (Ferguson et al., 2012; Howard et al., 2012; Kingma & van Dieen, 2004; Lardi & Frazer, 2003). However, this thesis found no difference in any shoulder or trunk moments between Supported and Non-Supported conditions. This could likely be due to a tradeoff between moment arm and force. There was an increase in force generation with Support compared to No Support (Figure 31). Presumably, when performing maximal hand forces, participants exerted within the maximum strength (i.e. moment) that they could produce with a given joint. Therefore, the increase in force was a direct result of a decrease in moment arm about the joints due to participants getting closer to the task handle. Thus, there was a tradeoff between force generation and moment arm, which ultimately explains the observed consistency in moments at the shoulder and trunk between Supported and Non-Supported exertions. Conversely, the previous studies noting a reduction in task shoulder and trunk moments with Support, only required submaximal hand forces (Cappelletto, 2013; Fewster, 2013). In those studies, task hand force was kept constant, so there was a benefit more of a realized benefit to reducing the moments via to the reduction in moment arm facilitated by external Support. In conclusion, in the current study, the benefit of external Support was realized more with increased force at the task hand, rather than decreasing task or support arm joint moments.

5.6 Precision Tasks

As another novel feature in this study, the Precision task was introduced as a variable to gain an understanding of how much lower force, but much finer hand control, could influence leaning and bracing behaviours. Overall, external support was used considerably less during these tasks compared to the gross motor, maximal hand force tasks. However, it was still employed for approximately half of the FSC trials (Figure 28). Since there was a very low (almost negligible) task hand force with this task, it is likely that any support strategies used for the Precision task were due to reasons other than generating oppositional forces (Fewster, 2013). First, Support may have been used to freeze the degrees of freedom of the lower half of the body. Based on Bernstein's (1967) Degrees of Freedom problem, this stabilization minimizes the need for control for part of the body (in this case, the legs), resulting in an improved ability to control movements at the upper limb and hand (to perform the nut-to-bolt task). Second, the Precision task took much longer to complete (approximately 6-8 seconds) compared to the maximal efforts (2-3 seconds) and, therefore, fatigue avoidance may have contributed to the participants' choice to support themselves during Precision tasks. Third, by supporting themselves, participants may have been able to get closer to the task element to improve their visual perspective when locating the nut to the bolt. Finally, participants may have used support as a preemptive means to push away from the apparatus, once the task was completed, to return to upright standing position, which is an effect that was speculated to be evident in the Anterior and Inferior exertion conditions (see 5.1.3.3).

Contrary to my hypothesis, there was no improvement in task performance (i.e. decreased task completion time) with Support. However, the number of errors associated with Supported vs Non-Supported trials was not recorded, and could have been a more appropriate measure of task performance. In previous studies, external support was associated with reduced errors in very fine motor surgical tasks (Galleano et al., 2006; Milerad & Ericson, 1994). Perhaps, external Support may not improve the speed of a task being performed, but may increase the likelihood that a task would be completed with higher quality due to increased whole-body stability.

5.7 Limitations and Future Directions

While it provided a more realistic work simulation, there was a disadvantage to having so many degrees of freedom with regards to stance and support surface availability. This likely resulted in higher between-subject variability. In previous studies that had more constraints, such as constrained participant footing and less support surface availability (Cappelletto, 2013; Fewster, 2013), there were fewer postural and support strategies available to participants to improve generate oppositional forces, or increase balance/stability. For example, when asked to exert a force at the two far Locations, the participants of the previous studies were more likely to adopt similar postures and support strategies to one another, since their feet were fixed. Furthermore, participants could use only one type of external support surface (i.e. either bracing,or leaning,), or no support at all. Conversely, in this thesis, participants could either not use support, or lean, brace, or simultaneously lean and brace. Next, in this thesis, participants could increase their base of support by either adapting/widening their stance, *and/or* using one *or more* of the support surfaces to gain stability. The variation in strategies could have resulted in greater variability between subjects, with regards to both kinematics and kinetics, and this made it very different to identify trends for certain outcome measures. A further confounding issue was that there were not even occurrences of support strategies as participants could choose one of: simultaneous leaning and bracing, leaning only, bracing only. Future studies/analyses should consider adopting a strategy similar to Jones (2011), who tested five different force-generation strategies (e.g. bracing only, simultaneous leaning and bracing, etc.), and was, therefore, able to directly compare outcome measures within those strategies. However, to maintain allow for an understanding of support choice, the first round of trials should still allow participants to freely choose their support/no support strategy.

Second, this thesis used a sample of young students that did not necessarily represent a working population. In reality, the working population is much older than the students who participated in this study, and they would have much more experience with the types of tasks being simulated. Given the aging workforce, companies and ergonomists are becoming increasingly concerned of how aging can affect strength and working behaviours. Future studies should consider using a population that is more representative of the workforce.

Third, the trials in this study were performed in isolation once every two minutes. This is very misrepresentative of industry, where multiple tasks are repeated at least once every minute throughout an 8-10 hour workday. Future studies should test how support strategies change with repetition and/or over a work day, as fatigue may influence the occurrence of external support.

For the fine motor tasks, there was no pressure placed upon the participants to complete the task with urgency. In industrial manufacturing settings, many workers are given a strict time limit to complete their series of tasks, and the consequences of not completing the tasks within their cycle time, due to errors or poor performance, are extremely costly. In future studies, researchers should consider shortening the time window allotted to the participants to increase the pressure to complete the task with accuracy.

The fine motor task used in this study had negligible hand forces. As an additional direction for studying Precision tasks and external Support, it would be interesting to test how submaximal task hand forces, with and without precision elements, could influence external support behaviours. This may reveal a potential interaction effect of Precision and force on external support probability. In fact, the Accuracy Effect (as explained previously) is evidence, which shows that support may improve the accuracy when performing tasks, since participants were more successful at reaching the required 90% directional threshold during maximal tasks when using Support.

6.0 CONCLUSIONS

This thesis contributed essential and novel knowledge to the literature, regarding how various task demands influence external support behaviours, and how external Support influences the body's ability to generate force at the task hand. First, three regression models were able to successfully predict the occurrence of various external support behaviours 74-86% of the time. As a novel feature, a model was developed that was able to predict the occurrence of simultaneous leaning and bracing. This thesis was also the first to show how external Support influences task hand force generating capacity in the intended Direction for a given effort, showing a 64% increase due to Support. It was concluded that external Support was used to generate oppositional forces to the task hand, and/or maintain balance throughout the exertion, and/or get the task shoulder closer to the task element. The results also supported the notion that external support frequency, and the forces applied, was related to the characteristics of force vector applied at the task hand. In generally, the leaning hand surface, chosen for a given condition, was the one that was perpendicular to the line of force generated at the task hand. Furthermore, the increase in horizontal reach for the task hand, increased the probability of the use of the horizontal surface. However, the horizontal and vertical leaning hand positioning also had a narrow range. Overall, these findings improve our understanding of the relationship between task demands, task hand force, and external the use of available support surfaces.

Compared to previous studies, this thesis minimized the experimental constraints with regard to stance, support and surface availability, and this increased the generalizability of these data to real-world scenarios. Therefore, these data will facilitate future DHM posture prediction algorithms that better able to incorporate external supports that are more appropriate for their intended workplace applications. Improved posture prediction models are essential to the ongoing paradigm shift towards proactive ergonomics for reducing cost and injury rates.

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APPENDIX A – Letter of Information and Consent Form

April 25, 2014

McMaster University
Inspiring Innovation and Discovery

Letter of Information and Consent

An Investigation of External Support Choices and Behaviours during One-Handed Tasks with Constrained Reaching

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Purpose of the Study
The goal of this study is to understand the support strategies that are adopted by humans during one-handed tasks. Specifically, we will evaluate the whole-body postures and forces employed by participants during different trial conditions. It is hypothesized that whole-body postures and force generation strategies will change during different task types, task hand locations, and support surface availability scenarios. We believe that support surfaces may present an opportunity for the non-task hand, thighs, or hips to externally support the body and generate force. By accounting for these strategies, more accurate posture prediction equations can be developed. The direct applications and implications of this research will be the improvement of ergonomic tools that are in use today. Currently, very important ergonomic decisions regarding job tasks with similar obstacles are being made with no validation on what the forces and 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

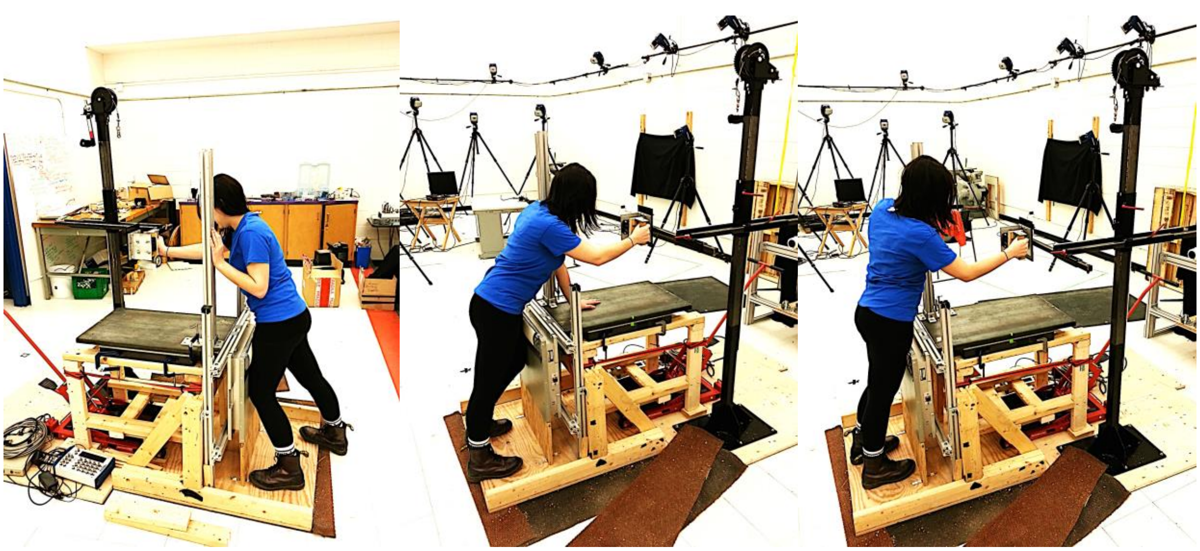
Participation in this study will involve three sessions in the McMaster Occupational Biomechanics Laboratory in the Ivor Wynne Centre, room A108. Before study commencement, physical characteristics such as height, weight, age, arm length, and foot length will have to be measured. This data will be kept confidential. You will be asked to wear a form fitting t-shirt or tank top with leggings or shorts.

Kinematic sensors and motion capture cameras will be used to determine your posture while performing the exertions. Fifty-two reflective markers will be taped onto various parts of your body and will be tracked in 3-D space by infrared light reflection. These cameras will only emit and capture infrared light, therefore only the reflection off of the markers is 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.

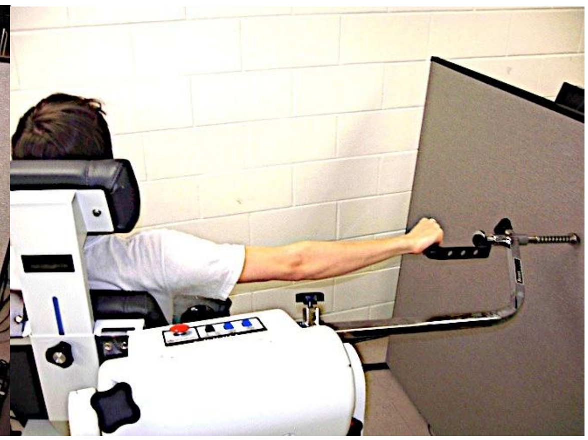
You will stand in front of the experimental apparatus. In most conditions, you will grip a handle (with your dominant hand) which is mounted to a force transducer. The force transducer will be used to measure the force that you are exerting on the handle. In other conditions, you will be asked to complete a precision task which involves correctly inserting a small object into a slot.

During the protocol, you will be either asked to apply a maximal force on the handle (in six directions), or complete the precision task. The tasks will be performed in four positions, in which the order to be performed will be randomized. These positions are comprised of two heights (55% of height and 75% of height) as well as two reaches (95% of arm length and 120% of arm length). Within each of the 4 hand locations, there will be 6 different force exertion directions (pull back, push forward, exert up, down, left, right), and 1 precision task. Each effort will last about 1-4 seconds. Each task type will be completed twice in each hand location, once with the support surfaces available for support, and once without support surfaces available for support. The choice will be up to you if you would like to use the support surfaces to help you complete the task when they are available.

In total, approximately 56 exertions will be completed during the study. In order to complete these exertions with adequate rest between trials, the entire protocol will occur in either one two-hour testing session, or two one-hour testing sessions.



On a separate day, 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 elbow and shoulder flexion/extension, shoulder 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. In addition to the Biodex, you will also complete two exertions of maximal handgrip using a handgrip dynamometer. Overall, the strength testing session should take about 30 minutes.



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.

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 $10 Tim Horton's gift card for each hour. The study will involve two to three data collection sessions, totaling approximately 2.5 hours.

Confidentiality:
You will be assigned a randomly generated subject code known only to the investigators; thus, your identity cannot 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 Julian Liebregts.

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. James Potvin and Julian Liebregts 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.

____

Signature of Participant

____

Name of Participant

APPENDIX B – Marker Locations and Skeletal Segments

Potvin et al (2008): Proactive Ergonomics Analysis Validation Study

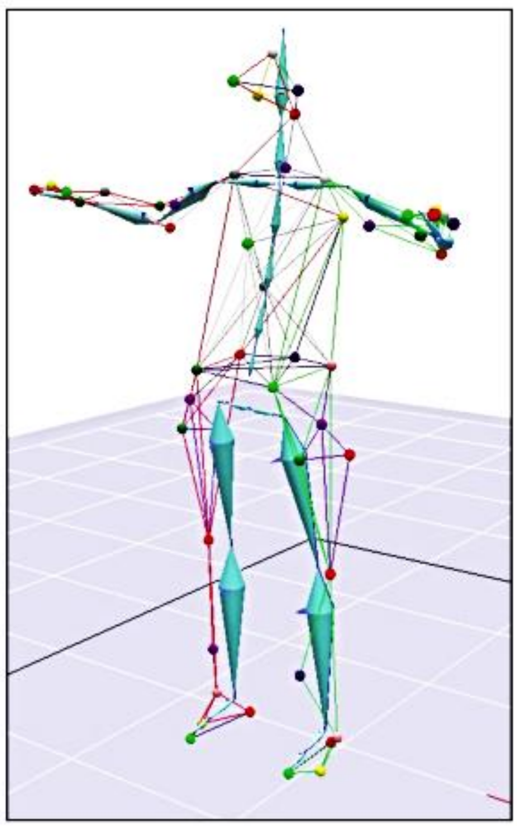
APPENDIX B: MARKERS

Marker Set for Motion Capture

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		

Skeletal Segments

1. Head
2. Head_markers
3. Left Clavicle
4. Left Foot
5. Left Hand
6. Left Hip
7. Left LowerArm
8. Left LowerLeg
9. Left Toes
10. Left UpperArm
11. Left UpperLeg
12. Neck
13. pelvis_markers
14. Right Clavicle
15. Right Foot
16. Right Hand
17. Right Hip
18. Right LowerArm
19. Right LowerLeg
20. Root
21. Right Toes
22. Right UpperArm
23. Right UpperLeg
24. Spine1
25. Spine2
26. Spine3
27. Spine4



APPENDIX C – ANOVA Structures

i. 2x4x6 Repeated Measures ANOVA (Gross Motor Tasks)

Support Presence		Support				No Support			
Task Hand Location		Low-Close	High-Close	Low-Far	High-Far	Low-Close	High-Close	High-Far	Low-Far
Gross Motor Task: Maximal Force Exertion	Superior	✓	✓	✓	✓	✓	✓	✓	✓
	Inferior	✓	✓	✓	✓	✓	✓	✓	✓
	Anterior	✓	✓	✓	✓	✓	✓	✓	✓
	Posterior	✓	✓	✓	✓	✓	✓	✓	✓
	Lateral	✓	✓	✓	✓	✓	✓	✓	✓
	Medial	✓	✓	✓	✓	✓	✓	✓	✓

ii. 2x4 Repeated Measures ANOVA (Fine Motor Task Only)

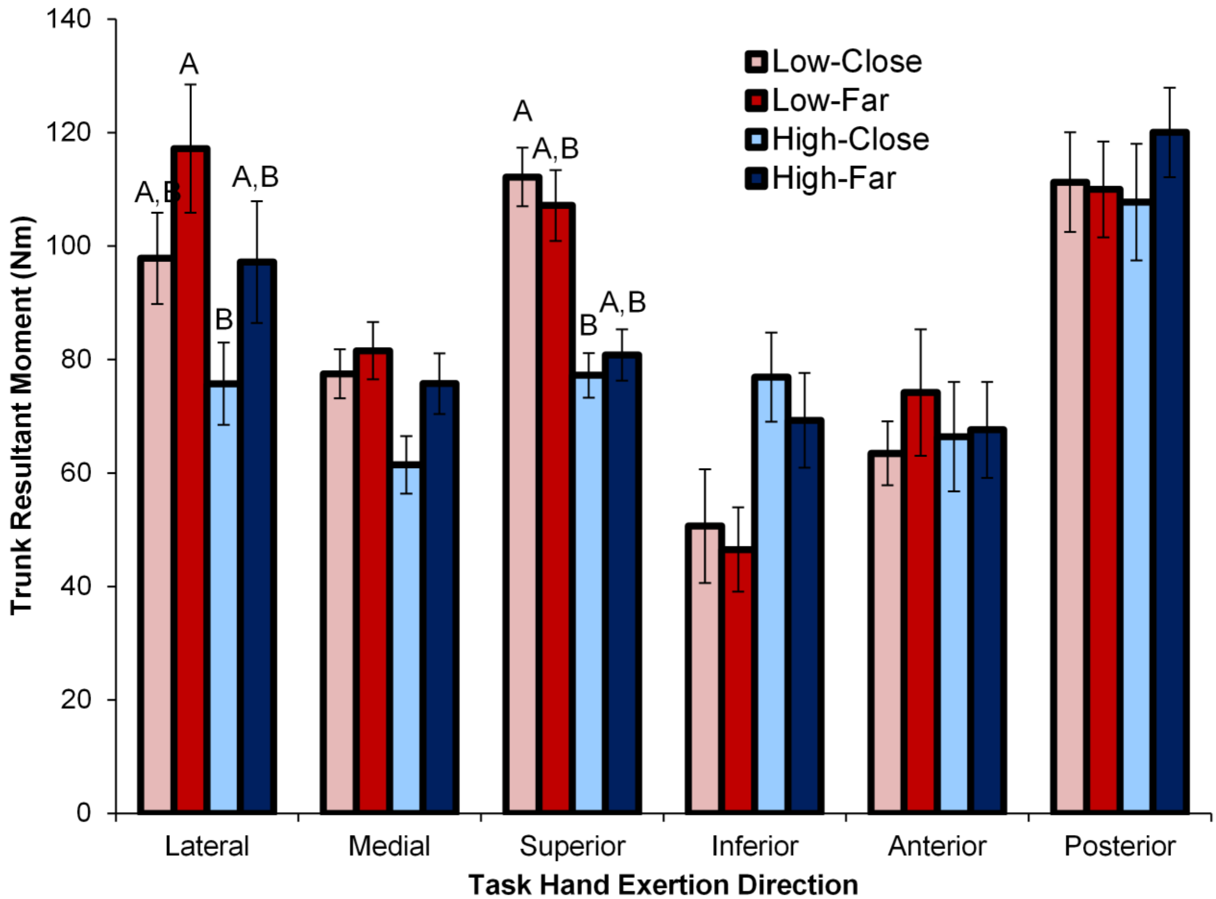
Task Hand Location		Low-Close	Low-Far	High-Close	High-Far
External Support	Support	✓	✓	✓	✓
	No Support	✓	✓	✓	✓

APPENDIX D – Participant Anthropometrics and Strengths

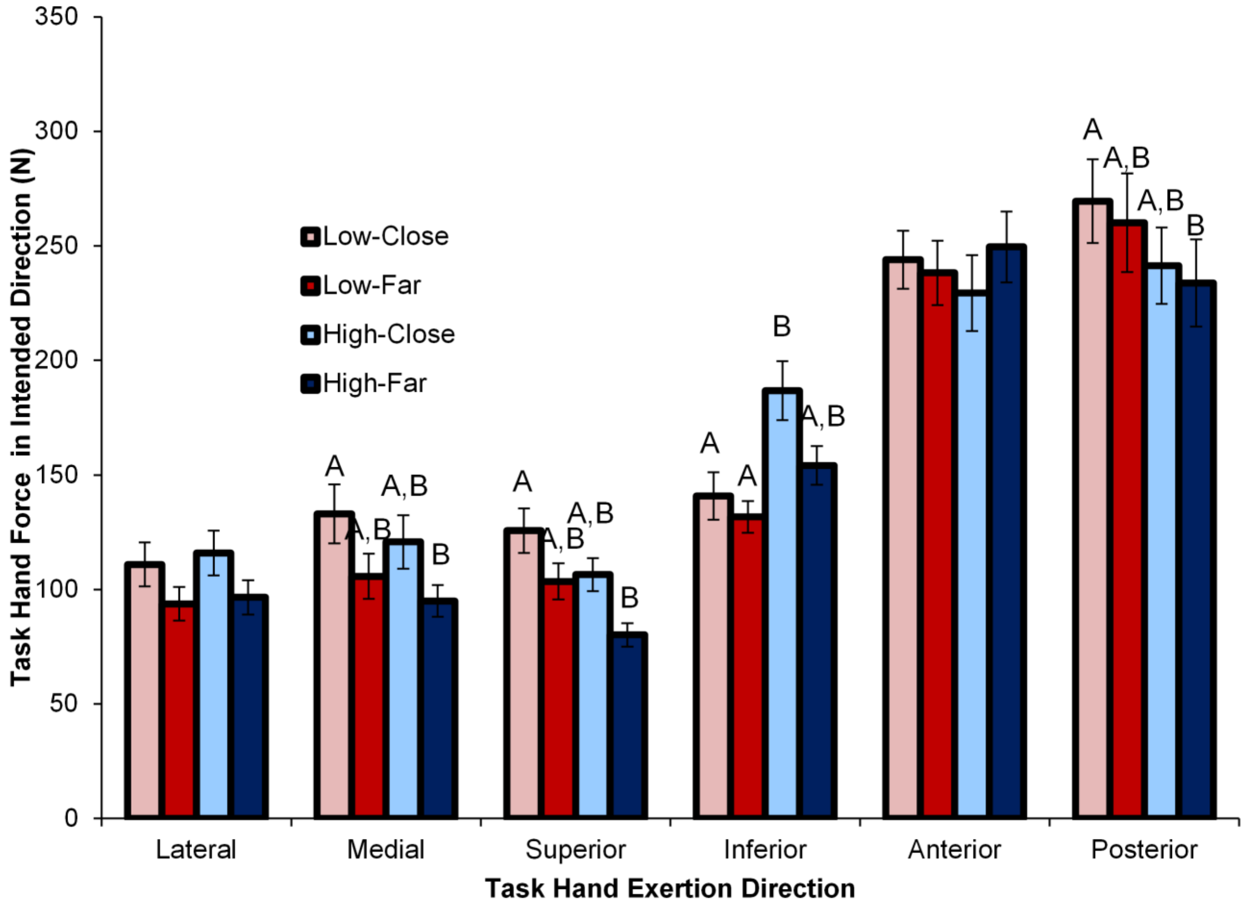
#	Height (cm)	Body Mass (kg)	Arm Length (cm)	Handgrip (N)	Elbow Flexion (Nm)	Elbow Extension (Nm)	Shoulder Flexion (Nm)	Shoulder Extension (Nm)	Shoulder Abduction (Nm)	Shoulder Adduction (Nm)	Trunk Flexion (Nm)	Trunk Extension (Nm)
1	166	52.2	70.0	315.0	41.9	23.1	36.7	48.4	31.5	45.3	137.7	142.9
2	170	54.8	70.0	317.0	26.8	30.2	38.7	66.5	27.7	59.3	155.7	180.2
3	168	53.3	70.0	285.0	26.0	25.1	34.8	44.5	29.4	41.4	155.7	154.8
4	158	48.3	64.0	281.0	23.3	23.1	25.6	42.2	19.0	37.3	119.0	110.8
5	167	59.2	72.0	321.0	29.8	37.8	45.1	63.3	36.5	43.2	169.4	96.4
6	172	68.2	71.0	341.0	36.1	33.0	43.2	63.4	36.0	55.5	233.5	237.2
7	170	59.5	70.0	413.0	37.2	37.2	68.8	76.4	36.1	54.7	191.3	139.0
8	180	75.6	76.5	327.0	37.8	36.7	45.6	66.1	46.3	55.8	244.3	301.4
9	165	44.0	67.0	284.0	25.1	18.6	73.9	30.9	24.0	37.5	117.8	107.1
10	167	72.7	69.0	372.0	49.9	45.7	42.7	38.1	50.3	61.8	238.4	175.1
11	167	47.7	70.0	302.0	33.4	43.0	47.6	73.5	35.8	64.9	151.3	67.1
12	170	65.8	69.0	321.0	42.3	37.4	46.5	60.8	35.5	41.3	170.3	145.7
13	166	55.2	68.0	310.0	36.5	35.4	44.9	66.8	30.4	55.4	155.6	158.6
14	173	71.6	75.0	376.0	51.5	48.5	53.4	81.8	48.5	89.8	226.5	247.2
15	166	50.2	69.0	263.0	29.2	32.3	27.3	48.7	24.8	49.7	143.7	63.7
16	183	95.9	79.0	309.0	40.5	34.7	52.7	57.7	57.2	59.2	276.7	138.0
17	169	56.1	69.0	281.0	39.2	28.9	37.0	52.7	21.6	52.3	165.8	133.5
18	170	60.0	70.5	302.0	37.8	43.0	42.9	67.5	40.9	68.1	176.4	160.0
Mean	169	60.6	70.5	317.8	35.8	34.1	44.9	58.3	35.1	54.0	179.4	153.3

APPENDIX E – Non-Support Significant Effects for Gross Motor Tasks

i. Two-way significant interaction effect of task hand Direction and task hand Location on trunk resultant moment



ii. Two-way significant interaction effect of task hand Direction and task hand Location on task hand force



APPENDIX F - Fine Motor Precision Task Supplementary Results

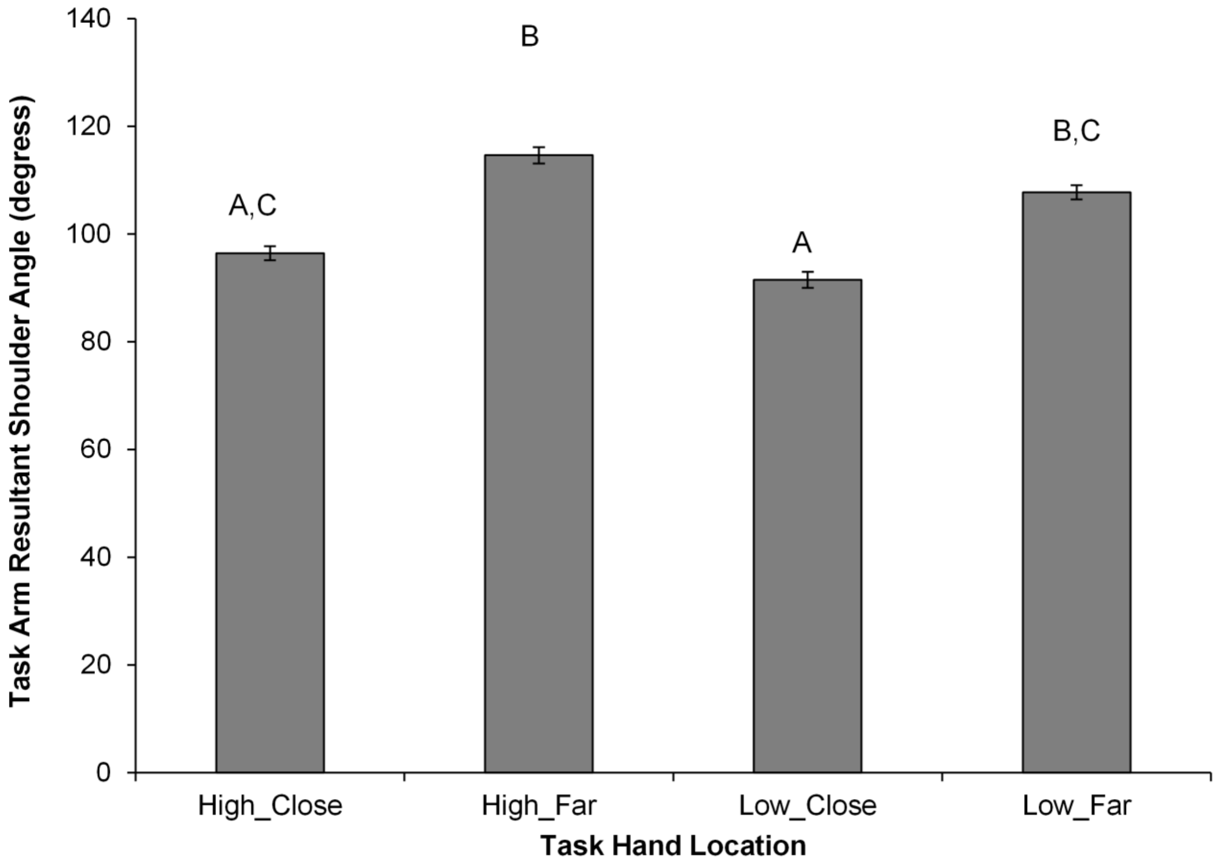
i. Summary of ANOVA Results

Variable	Support (n=144)	Hand Location (n=36)	Support * Location (n=18)
Task Elbow Flexion Angle	**0.0001 (0.255)**	**0.0001 (0.262)**	**0.0001 (0.053)**
Task Shoulder Resultant Angle	0.0823 (0.026)	**0.0001 (0.231)**	~~0.8510 (0.003)~~
Trunk Axial Angle	~~0.1980 (0.005)~~	**0.0001 (0.287)**	0.1505 (0.011)
Trunk Lateral Angle	**0.0003 (0.098)**	**0.0001 (0.098)**	0.1294 (0.010)
Trunk Resultant Moment	~~0.5326 (0.004)~~	0.0046 (0.068)	0.0012 (0.047)
Time to Complete Precision Task	0.4690 (0.031)	0.0870 (0.120)	~~0.0940 (0.005)~~

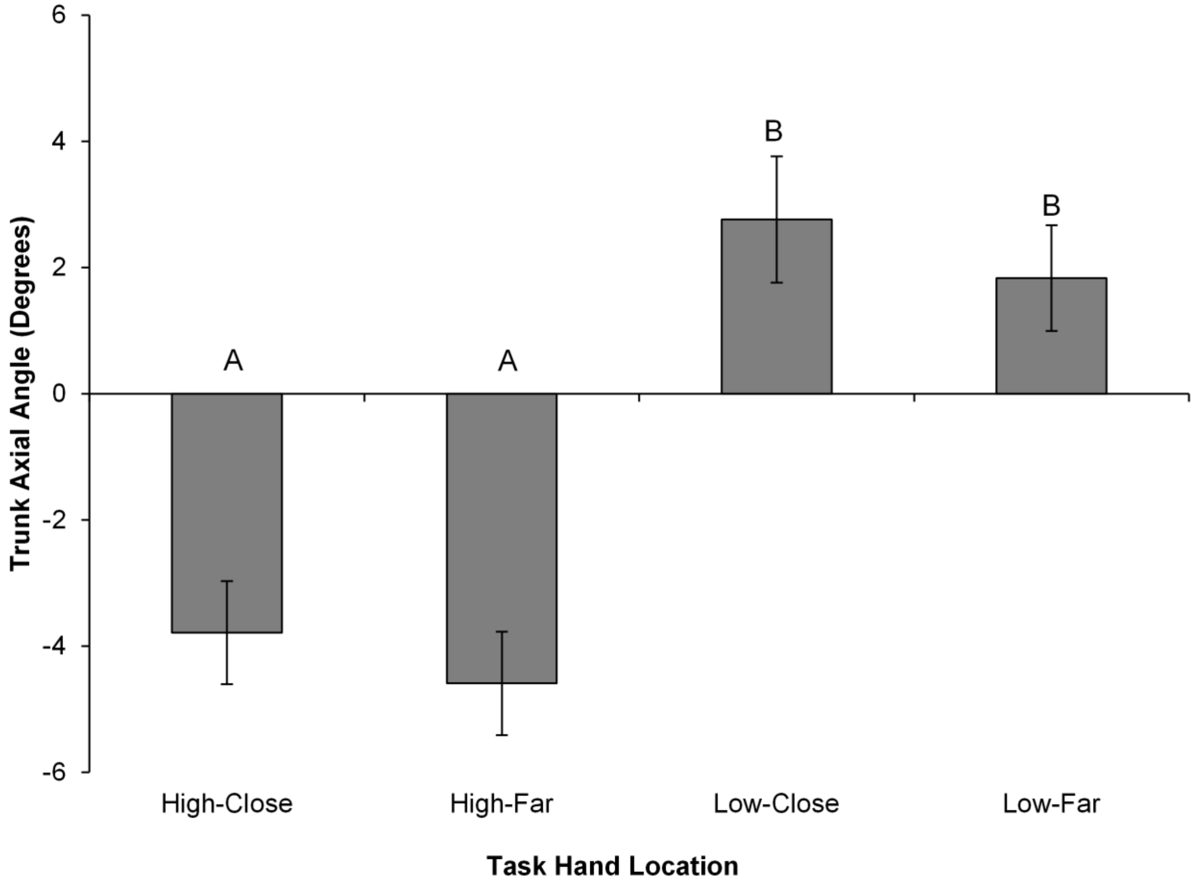
Legend
Discussed/Presented
~~Eta^2 < 1%~~
p < 0.001
p < 0.01
p < 0.05
p ≥ 0.05

Variable	Hand Location (n=36)
Bracing Resultant Force	0.7583 (0.011)
Leaning Resultant Force	**0.0005 (0.098)**
Leaning Elbow Flexion Angle	0.3655 (0.016)
Leaning Elbow Moment	0.3934 (0.029)
Leaning Shoulder Resultant Angle	0.0103 (0.068)
Leaning Shoulder Resultant Moment	0.7694 (0.012)

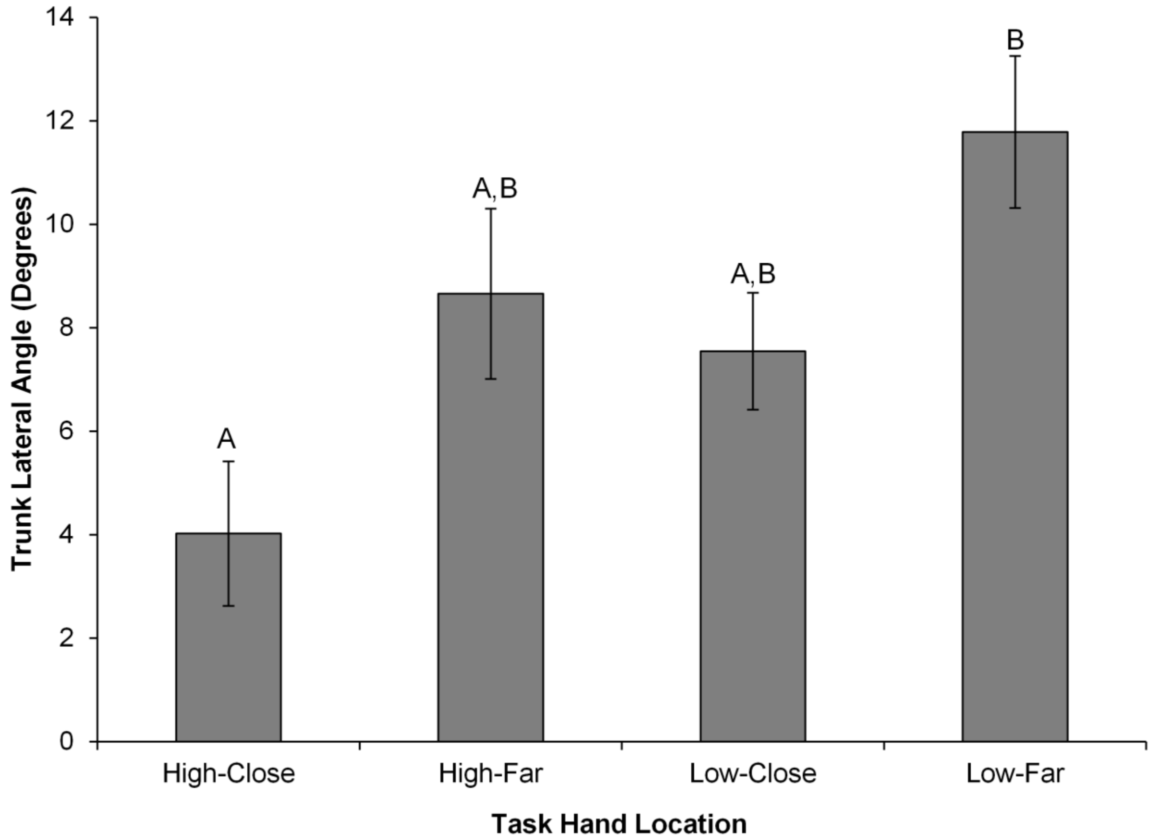
ii. Significant main effect of task hand Location on right shoulder resultant angle



iii. Significant main effect of task hand Location on trunk axial angle. A positive angle indicates left rotation, where the right shoulder is brought forward, while a negative angle indicates right rotation, where the left shoulder is brought forward.



iv. Significant main effect of task hand Location on trunk lateral angle



v. Non-significant main effect of hand Location on Precision task completion time