THE USE OF BRACING DURING EXERTIONS WITH EXTENDED REACHES

THE USE OF LOWER BODY BRACING DURING ONE-HANDED SUBMAXIMAL EXERTIONS WITH EXTENDED REACHES

By

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ABSTRACT

In many occupational tasks, environmental constraints limit how close a worker can place their body to a desired element of the task. Although this provides an obstacle when performing the task, workplace obstructions can often be used by a worker to externally support their body by means of bracing. The purpose of this thesis was to identify how a worker's posture would differ when the task must be performed with a constrained reach, compared to having the option to externally support against the thighs. At 4 different task hand Locations, subjects performed 6 exertions, comprised of 2 Loads (27.5 N and 55 N) and 3 Directions (Up, Down, and Pull). Subjects were able to choose if bracing would be used when performing the first 24 trial exertions. After the choice conditions had been collected, trials were performed again with a forced brace or unbraced. The most important finding of this study was that participants were twice as likely to brace when performing a task with a far reach. In addition, average brace forces were approximately 117 N for Up and Pull exertions, and were nearly half that (67 N) for Down exertions. Bracing location tended to shift in accordance with task hand location, that is, participants would brace at a lower height at low versus high locations. Flexing the trunk forward and twisting the right shoulder forward, combined with a more flexed task arm and reduced shoulder rotation, allowed participants to adopt a posture where their shoulder was closer to the point of exertion during braced exertions, thereby increasing their functional arm length.

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CHAPTER 1 – INTRODUCTION

Lost time injuries in the workplace, resulting from musculoskeletal disorders, are an issue affecting employees and employers alike. Often resulting from poor ergonomic design and control, these injuries are generally the result of excessive forces, working in awkward postures, and/or arise from the repetitive nature of a task. Since the arm is commonly used to apply a force in manufacturing tasks, injuries of this nature are particularly prevalent in the automotive manufacturing industry. In 2010, 5.2% of accepted lost-time claims were filed by workers in the automotive industry (WSIB Annual Report, 2010). Although the worker is using their hand as an end effector to manipulate the desired object, the whole arm is used to generate the force. Individual differences, combined with the many degrees of freedom in the upper body, lead to a vast array of postures being adopted by the workers to accomplish these tasks.

The Workplace Safety and Insurance Board (WSIB) stated in their Annual Report that there were a reported total of 235,791 injury claims in the province of Ontario in 2010, 60,179 that resulted in an accepted lost-time claim. Of these lost time claims, 11,704 (19.4 %) arose from injury to the upper extremity and 16,128 (26.8%) arose from injury to the low back. Although these numbers have steadily decreased by 5% and 3% respectively since 2001, it is important to strive to keep these statistics on a descending path in order to make the workplace a safe and healthy environment.

In recent years, automotive manufacturers have used digital human modelling technology in the work simulation process in order to perform ergonomic assessments (Chaffin, 2005; Dukic et al., 2007; Lamkull et al., 2007; Savin, 2011). With these technologies, the proposed work environment is digitally re-created and a digital manikin is manipulated within the environment, so that ergonomic analyses can be performed early in the manufacturing design process. The goal of work simulation is to identify and assess any risk of injury that may be present in the work environment long before a worker is placed within it, and often before the workstation is even built. This type of proactive, preventative ergonomics can be extremely cost effective as it often results in decreased risk of injury for the workers (Chaffin, 2002; Chaffin, 2005; Colombo and Cugini, 2005).

Although these technologies are heavily relied on, there is a large amount of inter-user variability in programs like HumoSim and Jack Static Strength Prediction (Dukic et al., 2007; Lamkull et al., 2007; McInnis et al., 2009; Savin, 2011). When using Jack (Siemens Corporation, Ann Arbor, MI) to perform an assessment, for example, the ergonomist must position and manipulate the manikin within the digital workspace. Slight variations in manikin posture have been shown to produce significantly different joint angles and percent capable value outputs (Chaffin, 2002; McInnes et al., 2009). There is a need to enhance the database of posture data by collecting a wider array of possible working scenarios so that working postures can be predicted using ergonomic software instead of selected by the ergonomist based on their best guess.

In manufacturing environments, workers are often faced with physical barriers when trying to complete various task demands. These workplace obstructions can limit the postures workers are able to adopt to complete their tasks by constraining how close a worker’s body is able to come to the desired element of the task. Although this provides an obstacle for the worker in regards to performing the task, workplace obstructions often deliver a surface upon which a worker can externally support their body.

External support is commonly categorized in terms of leaning and bracing. In the context of this thesis, “leaning” will refer to the use of the non-working hand or elbow for support, while “bracing” will refer to the use of other parts of the body to provide support. The thighs, pelvis, abdomen, and chest are common sites of body bracing. Damecour et al. (2010) observed that, when externally supporting the body by means of bracing, a worker can essentially increase the number of postures that they are able to adopt by increasing their functional reach beyond the capabilities present with no means of support, by allowing a greater forward displacement of the trunk. The forward displacement and increased reach distance proved to reduce the shoulder moment by decreasing the moment arm between the force vector and the shoulder (Damecour et al., 2010). They also found that bracing with the chest elicits a reduction in the activity of postural muscles (erector spinae, gluteus maximus, hamstrings, rectus femoris), resulting in decreased lumbar shear and compressive loading. Bracing at the pelvis resulted only in decreased activity of the rectus femoris.

The issue of workplace obstructions is particularly prevalent in the automotive manufacturing industry. Surveys of automotive assembly tasks have revealed a high incidence of leaning and bracing behaviours (Jones et al., 2008; Cappelletto et al., 2012). Workers in automotive manufacturing environments need to be able to maneuver in and around the frame of the vehicle to reach various parts and may not always have direct access to do so. In response, workers need to readily adapt their postures to overcome the barriers present in the task environment, making it common for workers to support these awkward postures by leaning with the contralateral hand or bracing with the body.

Jones (2011) extensively researched the effect that leaning and/or bracing had on the force generating capability of the task hand during one-handed exertions. Jones found that the availability of external support significantly increased the maximum force capability compared to a non-bracing condition. There was no significant difference between the force increases seen when the worker was leaning only, bracing only, or both leaning and bracing, thus exhibiting that any means of external support serves to increase force generating capacity. Jones postulated that the force-generating capacity associated with a posture is chosen as a function of the kinematic constraints imposed by: 1) the task environment (bracing availability, force requirements, task configuration), 2) the physical limitations of the worker (anthropometrics, physical limitations) and

3) biomechanical constraints present in the system (balance requirements, risk of falling, stability limits, sensitivity to joint loading).

Although it has been shown that these behaviours are a common practice in industrial workplaces, and that the capabilities of the task hand can be increased with the use of external bracing, little is known about the impact these behaviours have on postural adaptations made during exertions. Specifically there is a need to quantify the amount of force applied with the external bracing body part and the location of the bracing contact point. To improve the work simulation process, an accurate representation of these behaviours is needed.

Currently, it is difficult to perform a complete work simulation ergonomic assessment for a task that incorporates bracing behaviours, because when an unknown amount of force is applied by the bracing body part, a mechanically indeterminate system is created (Jones, 2011). Further, posture cannot be used to determine the amount of force applied at the external bracing body part (Jones, 2011). Ergonomic tools currently in practice, such as the Jack Static Strength Prediction program, are unable to compute important joint moments below the point of contact of the external bracing body part (Chiang et al., 2006; Jones, 2011). Consequently, there is a need to determine when and why a worker will adopt postures with external bracing so that, during an ergonomic simulation, choosing a posture is not based solely on the operator performing the assessment. In order to accurately predict when bracing behaviours will be employed during the performance of a task, it is necessary to record subjects performing exertions under similar conditions.

1.1 – Statement of Purpose

The primary purpose of this thesis was to determine when and where a worker will brace during one-handed tasks with varying task hand: 1) locations, 2) force levels, and 3) exertion directions. This study also aims to quantify the amount of force used for bracing. Furthermore, this study aims to identify how a worker's posture would differ when the task must be performed with a constrained reach, compared to having the option to externally support against the thighs. The overall goal of this study is to compare kinetic and kinematic variables, including joint angles and moments at the elbow, shoulder, and trunk, for tasks with extended reaches when external bracing is or is not employed. Not only will this allow for a quantification of forces at the external bracing body part, it will provide insight as to the postural changes that occur when workplace obstructions can be used for external bracing. This data will be used to further develop the library of postures that can later be used in posture prediction algorithms, with the intention of improving the simulation of occupational tasks in which environmental constraints or obstacles are present.

CHAPTER 2 – LITERATURE REVIEW

2.1 – Constrained Reaching

An exertion can be considered as having a constrained reach if there is a physical barrier present in the work environment that limits how close a worker is able to get their body in relation to the desired task effector. In addition, in a constrained reach, the worker does not use this obstacle to support their body during the performance of the task. If the worker does support their body on the limiting structure, this can be deemed as bracing and will be discussed in the following section (2.3). Constraints on posture, as may arise during automotive manufacturing, can affect the amount of force a worker can produce (Chaffin et al., 1983). There is little research in this area, however.

Noting that certain workspaces have a tendency to constrain a worker's posture, Haslegrave et al. (1997) collected maximal one-handed exertion data for common awkward postures seen in industry. The focus of the study was postures that incorporated a lateral bend or overhead task hand position. These postures were referenced to a standard position, which was essentially an exertion with a constrained reach. For these exertions, the participant's right foot was constrained at a horizontal distance from the task hand equal to the subject's maximum reach. Up to this point in the literature, the position of both feet was constrained in similar exertions (Rohmert, 1966; Warwick et al, 1980). The exertions in the standard conditions were performed in front of the body at shoulder height in a pushing direction. The authors compared the amount of force produced in the standard position in their study to that produced in the similar position in Rohmert (1966), with the exception that both feet were constrained. It was noted that subjects were able to produce about 33% more force in Haslegrave et al.'s trials. The authors attributed this difference to the slight difference in foot constraint between the two studies. The main finding of

Haslegrave et al. (1997) is that the force exerted by the task hand is affected by even minimal posture constraints.

Kingma and van Dieen (2004) investigated the effects that lifting over an obstacle had on trunk loading and kinematics. They compared two-handed lifting to one-handed lifting, with and without support of the contralateral hand. There was a reduction in total net moment at the L5/S1 joint by 10% in a one-handed lift over and obstacle compared to a two-handed lift. It was noted that postural adaptations, including an increase in lateral bending and twisting of the trunk and a decrease in trunk flexion, occurred when only one hand was used for lifting (Kingma and van Dieen, 2004). When a reach is constrained and no surface for external support is available, force generating capacity when pulling stems from using one's own body weight, by shifting the pelvis backward (Jones, 2010).

2.2 – External Bracing

External support, through the use of body bracing, has been shown to affect the posture of a worker as well as the amount of force that they can exert at the task hand (Kroemer, 1978; Ferguson et al., 2002; Damecour et al., 2010; Jones, 2011; Damecour et al., 2012). It has been postulated that the worker is able to adapt to the physical environmental constraint by incorporating a bracing behaviour into the chosen posture as a strategy to generate an increased amount of force with the task hand (Jones, 2011). Bracing increases force magnitudes at the task hand by creating an oppositional force with the bracing body part in pulling and pushing tasks (Kroemer, 1974; Pheasant et al., 1982; Jones, 2011)

Jones (2011) extensively researched the effect of leaning and/or bracing on the force generating capability of the task hand during one-handed exertions. Participants performed maximal and submaximal (50%) exertions in 4 task hand (TH) locations; high TH height with a close reach, medium TH height with a close reach, medium TH height with a far reach, and low TH height with a close reach.

In each of these locations, each exertion was performed in up to 5 directions; exerting right, exerting left, pushing, pulling, and exerting upwards. These exertions were repeated with: 1) no level of leaning and/or bracing, 2) with leaning only, 3) with bracing only, and 4) with both leaning and bracing. Jones found that the availability of external support lead to an average increase of 40% in force compared to trials with no bracing. It is important to note that the downward exertion direction was not measured in any task hand location.

Jones (2011) also postulated that a posture is chosen as a function of the kinematic constraints imposed by the task environment, the physical limitations of the worker, and biomechanical constraints present in the system. These factors can be seen in Figure 2.1 and were derived by Jones based on several studies (Grieve and Pheasant, 1981; Pheasant et al, 1982; Chaffin et al., 1983; de Looze et al., 2000; Hoozemans at al., 2004; Granata and Bennett, 2005; Boocock et al, 2006). Jones came to the conclusion that bracing forces, and the postural adaptations associated with these behaviours, are the result of interactions between: a) task hand position, b) bracing availability, c) force direction, and d) exertion magnitude. These variables, inherent to the physical constraints imposed by the task, were the foundation upon which she built her posture prediction algorithms. Jones deemed the resulting posture to be chosen as a means to generate force and classified such force generating strategies in terms of the level of bracing availability and whether the bracing force created an oppositional or adjacent vector to the task hand.

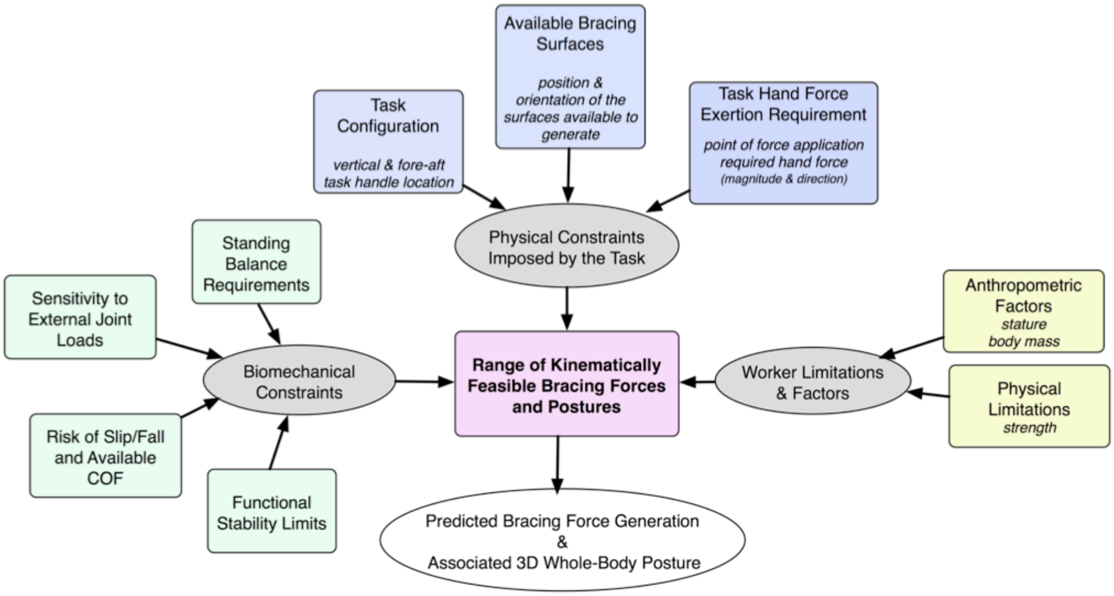


Figure 2.1: Factors proposed to affect force-generating strategies in one-handed exertions with the availability of a bracing surface. From Jones (2011).

Postural adaptation, as a response to an altered force generating strategy, has been shown with varied bracing heights (Damecour et al., 2010; Damecour et al., 2012). As the height of the brace was increased from the pelvis to the abdomen, the subjects' trunk movement pattern showed a shift from a hip-dominant to a spine-dominant strategy, demonstrating a trade-off between having a neutral spine posture versus decreased L4/L5 loading (Damecour et al., 2012). Likewise when the worker used a table-edge to brace, compared to a dynamic trunk support placed on the ribcage, the same trends were exhibited (Damecour et al., 2010). These researchers suggest that bracing is a way to increase the functional reach of a worker, thereby increasing the number of postures that can be used to complete a task. Although this increase may benefit the worker in terms of enabling them to choose the most comfortable posture, it makes it difficult for an ergonomist to try and predict the posture that will be chosen during an analysis.

2.3 – External Support in the Automotive Industry

Two surveys of automotive assembly tasks have recorded a high number of leaning and bracing behaviours (Jones et al., 2008; Cappelletto et al., 2012). Jones et al. (2008) surveyed 20 jobs and observed some use of external support (lean and/or brace) in 48% of the task elements contained in these jobs. Of the task elements with external support, 64% of elements included a component with body bracing. These elements can further be broken down as follows: 15% were one-handed exertions with bracing, 30% were two-handed exertions with bracing, and 19% were one-handed exertions with contralateral leaning and body bracing. The authors went further to report that, in addition to leaning with the contralateral hand, 88% of postures exhibited at least one site of body bracing. The most common sites of bracing were the pelvis (44%), abdomen (25%), and thighs (12%). Although this survey provided much needed insight into the prevalence of leaning and bracing in the automotive industry, its limitations include the small number of jobs surveyed (20), relative to the total number in an auto assembly plant, and the attempt to explicitly include jobs which indeed had a contact surface present in the environment. In addition, it was not documented at what height the bracing behaviour occurred or the amount of force that may have been used by this body part.

Expanding upon this work, Cappelletto et al. (2012) surveyed an additional 250 jobs. These authors observed that 101 jobs (40%) exhibited postures with some form of external support. Bracing behaviours were seen in 43% of these jobs, broken down as follows: 6% were one-handed exertions with bracing only, 16% were two handed exertions with bracing only, 20% were one-handed exertions with both leaning and bracing, and 1% were two-handed exertions with both leaning and bracing. This distribution is shown in Figure 2.2.

The thighs were the most common body part used for bracing and were used in 50% of task elements with bracing. The abdomen (19%), chest (14%), and pelvis (14%) were also frequently used. Further, the external bracing body part made contact with the rocker panel of the vehicle in 40% of exertions. It was measured that bracing occurred most frequently at a height of 50 cm, which corresponds to an area just above the knee for an average female. Figure 2.3 illustrates the frequency of leaning and bracing behaviours observed for different absolute heights and also depicts these positions relative to an average male and female automotive worker as shown by Jack and Jill manikins.

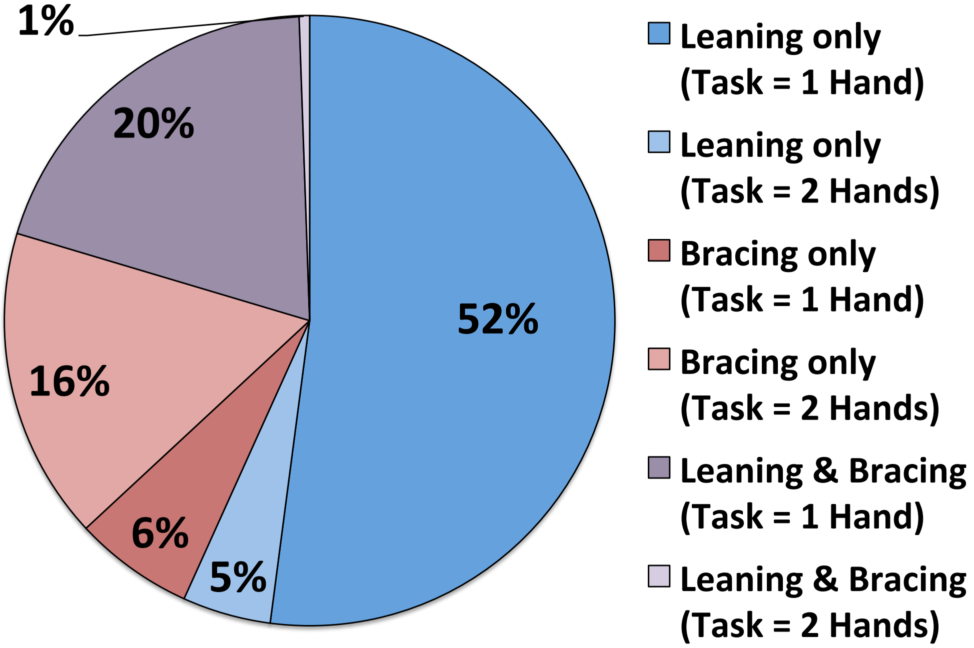


Figure 2.2: The breakdown of external support types by the number of task hands used, for the jobs with observed leaning and/or bracing. The blue portions of the pie chart represent leaning only (57%), the red portions represent bracing only (22%), and the purple portions represent a combination of both leaning and bracing (21%). Task = 1 Hand indicates that only one hand was used to complete the task element. Task = 2 Hands indicates that both hands were needed to complete the task element. From Cappelletto et al. (2012).

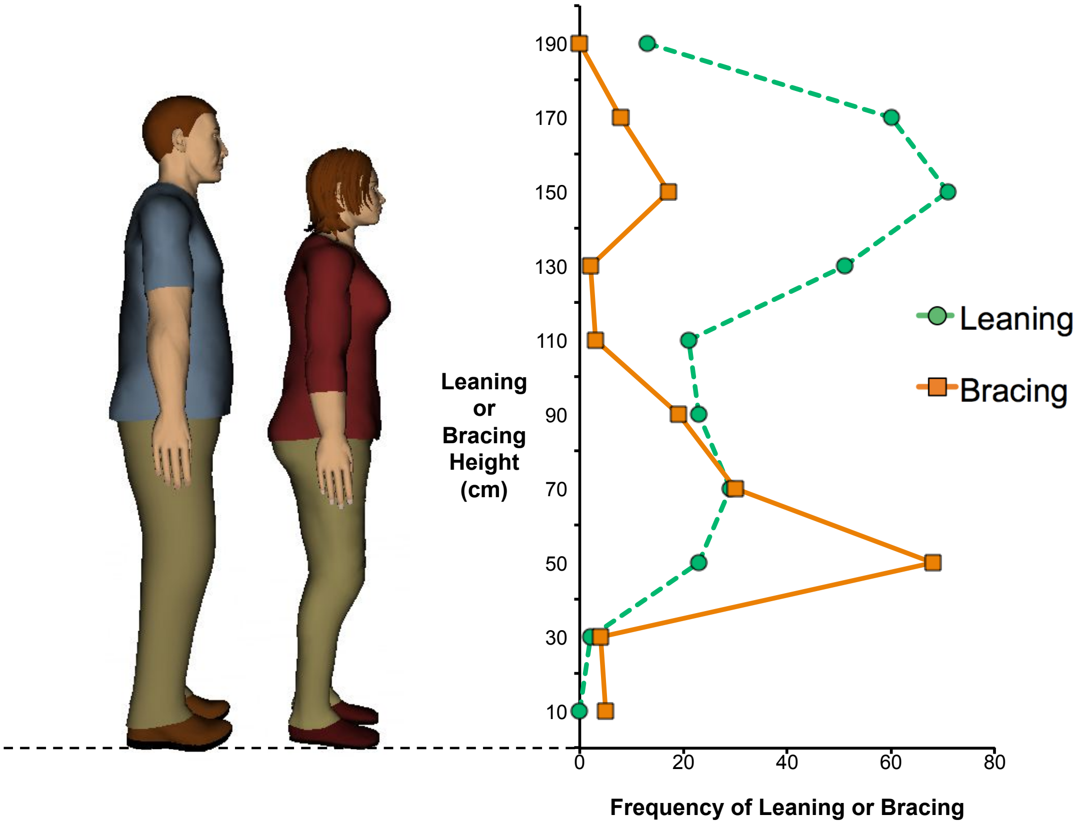


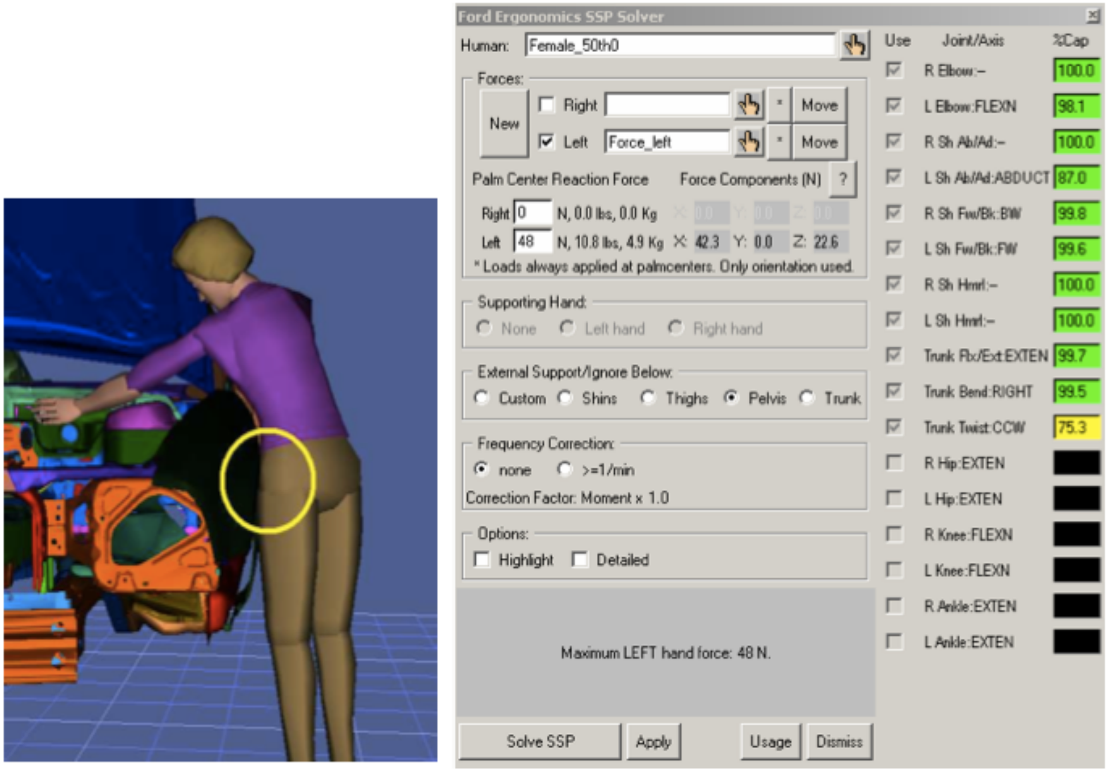
Figure 2.3: This figure shows the frequency distribution of leaning and bracing heights observed in the survey. A model of both an average female and average male automotive assembly worker are also depicted so that these heights can be interpreted relative to where they would be located on an actual worker. Note that, for an average female worker, bracing occurred most frequently around thigh-level. From Cappelletto et al. (2012).

Cappelletto et al. (2012) also recorded the direction of force exerted by the task hand in the survey. A force was most frequently exerted in the upward and downward directions with the use of a power grip posture. Although this survey did capture a wider, and more randomly chosen, range of jobs, it did not document how much force is applied by the external bracing body part.

2.4 – Evaluation of External Bracing in the Automotive Industry

Ergonomic software tools are used in the automotive manufacturing industry to help determine the maximum acceptable force that can be exerted by a worker. The goal of this is to maximize production efficiency while minimizing risk of musculoskeletal disorders for the worker. The biomechanical software 3D Static Strength Prediction Program (3DSSPP), which was developed by the Center for Ergonomics at the University of Michigan is widely used in ergonomic practice. This software was created to evaluate the physical demands of a task, by determining the moments on individual joints of the body and the compression forces of the spine for specific postures. Co-ordinates of the hand positions measured from the worker during the task, as well as hand loads, can be inputted into the software and used to posture a digital manikin. Biomechanical modeling is then used to determine static joint moments for the given posture. A direct quantification of the percentage of a desired population that would be capable of attaining these postures is given for each joint. The software also provides compression forces at the L5-S1 joint. The goal is to ensure that, for a given posture, all joint percent capable values fall below a certain threshold, usually set at 75% of females. A limitation inherent in this program is the possibility to slightly alter a working posture that has been deemed unacceptable until a posture has been achieved which meets the necessary guidelines and still possesses the same task hand characteristics (Chaffin and Erig, 1991). This iterative process may be able to yield a job that is “acceptable”, however it is not necessarily representative of how a human would perform the task in the same scenario.

The Jack Static Strength Prediction tool (JSSP) is an ergonomic software based on 3DSSPP that is used by the Ford Motor Company to conduct ergonomic analyses (Chiang et al., 2006). The Ford Ergonomics Static Strength Prediction Solver (FSSPS) was an addition to JSSP that aimed to improve the workflow process by outputting the maximum acceptable hand loads for a certain posture. With this, the iterative process is eliminated and a force value is given for a particular posture. The program has since been incorporated into JSSP itself and is now known as the ForceSolver. In addition to hand force inputs used by 3DSSPP and JSSP, the ForceSolver incorporated two unique inputs with the ability to identify the use of external support in the system. There is the ability to account for the use of a supporting hand (none, right, left), and the ability to select a part used for body bracing (none, shins, thighs, pelvis, trunk). If an ergonomist intends to analyze a posture identified to have body bracing, one of these options can be chosen. Since externally bracing with a part of the body creates a statically indeterminate system, the external bracing forces cannot be calculated (Chiang et al., 2006; Jones, 2011). As a result, ForceSolver is unable to calculate percent capable values for joints located below the point of body bracing (Chiang et al., 2006). Figure 2.4 shows an FSSPS window from Chiang et al. (2006) for the analysis of worker reaching into the engine compartment and bracing against the fender with their pelvis. It can be seen that the percent capable values for all joints below the trunk are invalidated and blacked out. JSSP's ForceSolver has added features such as standing force distribution strategy and improved frequency and duration inputs in addition to the features that are shown in the FSSPS in Figure 2.4.



Human: Female_50th0

Forces:
☐ Right
☑ Left Force_left

Palm Center Reaction Force Force Components (N)
Right 0 N, 0.0 lbs, 0.0 Kg X: 0.0 Y: 0.0 Z: 0.0
Left 48 N, 10.8 lbs, 4.9 Kg X: 42.3 Y: 0.0 Z: 22.6
* Loads always applied at palmcenters. Only orientation used.

Supporting Hand: ○ None ○ Left hand ○ Right hand

External Support/Ignore Below: ○ Custom ○ Shins ○ Thighs ● Pelvis ○ Trunk

Frequency Correction: ● none ○ >=1/min
Correction Factor: Moment x 1.0

Options: ☐ Highlight ☐ Detailed

Maximum LEFT hand force: 48 N.

Use	Joint/Axis	%Cap
☑	R Elbow:–	100.0
☑	L Elbow:FLEXN	98.1
☑	R Sh Ab/Ad:–	100.0
☑	L Sh Ab/Ad:ABDUCT	87.0
☑	R Sh Fw/Bk:BW	99.8
☑	L Sh Fw/Bk:FW	99.6
☑	R Sh Hmrl:–	100.0
☑	L Sh Hmrl:–	100.0
☑	Trunk Flx/Ext:EXTEN	99.7
☑	Trunk Bend:RIGHT	99.5
☑	Trunk Twist:CCW	75.3
☐	R Hip:EXTEN	■
☐	L Hip:EXTEN	■
☐	R Knee:FLEXN	■
☐	L Knee:FLEXN	■
☐	R Ankle:EXTEN	■
☐	L Ankle:EXTEN	■

Figure 2.4: Left) Posture of a female manikin in Jack performing an exertion inside the engine compartment. Here, she is externally supporting herself by bracing against the fender with her pelvis. Right) A sample output from Force Solver analyzing the posture shown on the left. The pelvis is selected in the external support input section, invalidating all outputs below the trunk, as shown in black. Adapted from Chiang et al. (2006).

The inability to identify joint loading outputs below the point of body bracing is a limitation of the FSSPS, which in turn limits the validity of risk assessments in the proactive work simulation process. There is a need to for a better method of conducting ergonomic analyses in postures where body bracing behaviours are present. There is also a need to record the amount of force used by the worker to externally brace. By doing this, we can better understand the joint reaction forces that occur with the postural adaptations inherent in bracing behaviours.

CHAPTER 3 – METHODS

3.1 – Participants

A total of 18 right-handed, healthy females were recruited from the McMaster University population to participate in this study. Since ergonomic standards are set to be acceptable to 75% of females, only females were used in this study. The average age of participants was 22 ± 1.9 years and the average height of 166.1 was at the 74th percentile of the population mean. All subjects were free of any musculoskeletal disorders or injuries. Subjects were asked to wear a form-fitting t-shirt or tank top, shorts or leggings, and non-reflective shoes for the duration of the study. Descriptive anthropometrics can found in table 3.1.

Table 3.1: Anthropometric data of participants included in study (n=18).

	Age (yrs)	Weight (kg)	Height (cm)	Arm Length (cm)
Mean	22.2	64.6	166.1	71.8
St. Dev.	1.9	11.3	8.6	4.5
Min	19	47	150	63
Max	26	86	180	79

Prior to participation, participants were required to read and sign a consent form which disclosed the nature of the study as well as any potential risk factors that may be associated with the tasks being performed (Appendix A). All portions of this study were approved by the McMaster University Research Ethics Board.

3.2 – Instrumentation and Data Acquisition

3.2.1 – Experimental Set-Up

Two tri-axial load cells (500 lb. XYZ Sensor, Sensor Development Inc., Lake Orion, MI) were used to measure and record force exertion data. The first load cell was mounted beneath the task hand effector and was used to record force exertions in each task hand location. This load cell was mounted with a padded D-shaped handle. The task handle and load cell was attached to a vertical piece of slotted rail that sat atop a horizontal piece of slotted rail (80/20 Inc., Columbia City, IN). The inverted T-shaped orientation of slotted rail allowed both the horizontal reach distance and vertical task height to be controlled. A second, larger, vertically-mounted load cell (AMTI force plate) with foam padding along the superior border was used as a bracing surface. A load cell was chosen as the bracing surface so that force magnitude and direction data applied by the bracing body part could be collected. The superior border of the bracing surface was placed at 50% of each participant's height to allow for bracing with the thighs. A schematic and photo of the experimental set-up can be seen in Figures 3.1 and 3.2

All force data was collected at 400 Hz using custom LabVIEW software (National Instruments, Austin TX). A PC compatible computer was used for data collection and converted using a 16-bit A/D converter (National Instruments, Austin TX).

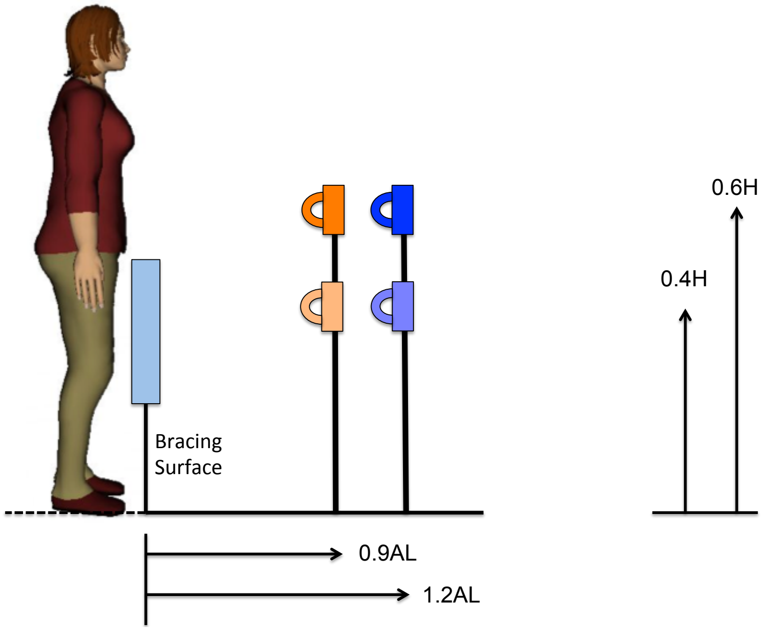


Figure 3.1: Schematic of the experimental apparatus. Note that all 4 task hand locations are shown as a combination of vertical distance (relative to subject height - H), and horizontal distance (relative to subject arm length - AL).

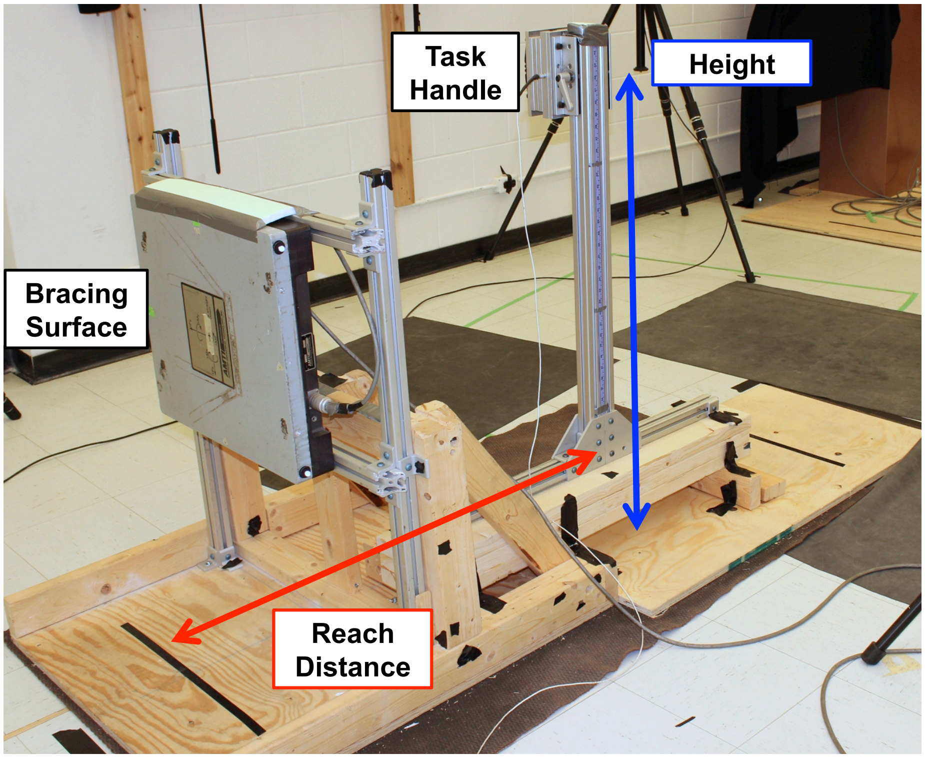


Figure 3.2: Photograph of the experimental apparatus. Horizontal task location is shown in red and vertical task location in shown in blue.

A total of eleven Raptor-4 digital infrared cameras (Raptor-4. Motion Analysis Corporation, Santa Rosa, CA) were used to collect kinematic data. Kinematic data was collected and sampled at a rate of 60 Hz using motion capture software (Cortex 3.6.1, Motion Analysis Corporation, Santa Rosa, CA). Reflective markers were placed on 52 landmarks, enabling a digital representation of the entire body comprised of 27 skeletal segments, as defined in Potvin et al (2008). Exact marker placement locations are listed in Figure 3.2 and depicted in Figure 3.3.

Table 3.2: Locations of the 52 reflective markers used with the Raptor-4 camera system.

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

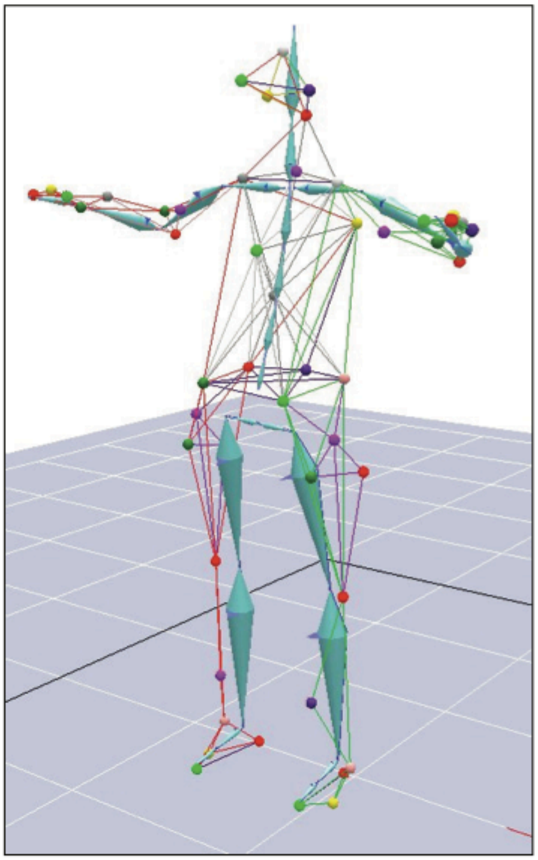


Figure 3.3: Representation of the marker locations and the 23 skeletal segments.

3.2.2 – Standardized Strength Testing

An isokinetic dynamometer (Biodex 4, Biodex Medical Systems, New York, USA) was used to conduct standardized strength tests. Strength data were collected at 100 Hz. The dual position back extension/flexion attachment was used to measure isolated lumbar flexion and extension and was adjusted to manufacturer specifications for each participant. The shoulder attachment was affixed to the Biodex and was used to measure shoulder flexion and extension strength as well as abduction and adduction strength. The elbow attachment and limb support pad were used to measure elbow flexion and extension strength.

3.3 – Experimental Protocol and Procedures

3.3.1 – Participant Preparation and Familiarization

Anthropometric measurements of height (cm) and arm length (cm) were recorded in order to determine individualized task parameters for each participant. Arm length was defined as the distance from the acromion process to the tip of the 3rd distal phalanx when standing in anatomical position. Height and arm length data were entered into a spreadsheet where task hand locations and brace plate height were calculated

Subjects were asked to arrive dressed in the appropriate clothing to allow correct marker placement. Prior to data acquisition, 52 reflective markers were placed on the participant in accordance with the locations listed in Figure 3.2, for use with the infrared motion capture cameras.

The motion capture system was calibrated prior to participant arrival. The participant was asked to stand in a T-position to ensure all markers were visible to the cameras. This posture was also recorded and used as a template to build the skeletal segments. Next, participants were asked to perform a series of motions throughout the capture volume. This included arm circles, forward bending of the trunk, forward reaching of the arms, and a series of squats and lunges. The range of motion was recorded and used ensure adequate marker tracking was achieved.

Participants were then guided through a series of practice exertions. To ensure that the requested task hand force was produced, an auditory cue would sound once the resultant force reached the indicated threshold. Participants were instructed to gradually exert against the handle until the sound was heard, at which time the exertion could be terminated. Participants were able to practice until they were comfortable with the auditory feedback mechanism. At this time, participants were also informed of the bracing surface. They were instructed to perform the exertion in a natural manner and that if they needed extra support, the surface could be used. They were then guided to practice exertions with and without the use of bracing and asked to choose whatever method felt most natural for the remainder of the session.

3.3.2 – Protocol for Acquisition of Experimental Trials

Once subjects indicated they were comfortable to proceed, acquisition of the experimental trials commenced. Exertions were performed at 4 task hand locations, comprised of 2 vertical task hand heights, determined as a percentage of subject height (H), and 2 horizontal task hand reach distances, determined as a percentage of subject arm length (AL) (Figure 3.1 a). These Locations were Low-Close (0.4H, 0.9AL), Low-Far (0.4H, 1.2AL), High-Close (0.6H, 0.9AL), and High-Far (0.6H, 1.2AL). The participant's ankle position was used as the 0 cm location when setting horizontal reach distances and was indicated by a black line on the base of the apparatus. Participants were able to determine the positioning their feet as long as their ankles fell over the black line.

At every Location, subjects performed 6 exertions, comprised of 2 Loads (27.5 N and 55 N) and 3 Directions (Up, Down, and Pull) (Table 3.3). Participants exerted against the task handle in the specified direction until the auditory cue was sounded. The trial was accepted if at least 90% of the resultant force was in the requested direction. Trial order was randomized, blocked by Location.

Table 3.3: Summary of the 24 trial exertions shown as a combination of Location, Direction, and Load.

Location	**Load (N)**	**Direction**		
		Up	Down	Pull
Low-Close	27.5	X	X	X
	55.0	X	X	X
Low-Far	27.5	X	X	X
	55.0	X	X	X
High-Close	27.5	X	X	X
	55.0	X	X	X
High-Far	27.5	X	X	X
	55.0	X	X	X

Each of the 24 aforementioned conditions were performed standing in front of the bracing surface which was set with the top of the force plate at 0.5H (Figure 3.4). Subjects were asked to perform the exertion in the way that felt most natural. That is, they were able to choose whether or not they braced for the first trial of each condition. After the first trial of each of the 24 conditions had been collected, trials were performed again with or without bracing (depending on what had been chosen for the first trial) (Figure 3.5). For example, trials where the participant initially chose to brace were re-collected using the side of the apparatus without a bracing surface (unbraced) (Figure 3.6). In total, each participant completed 48 exertions such that there was a Brace and No Brace trial for each Location, Direction, and Load combination. Each exertion was collected for 6 seconds. Subjects were given 30 seconds of rest between exertions. All 48 trials were collected in one two-hour session.

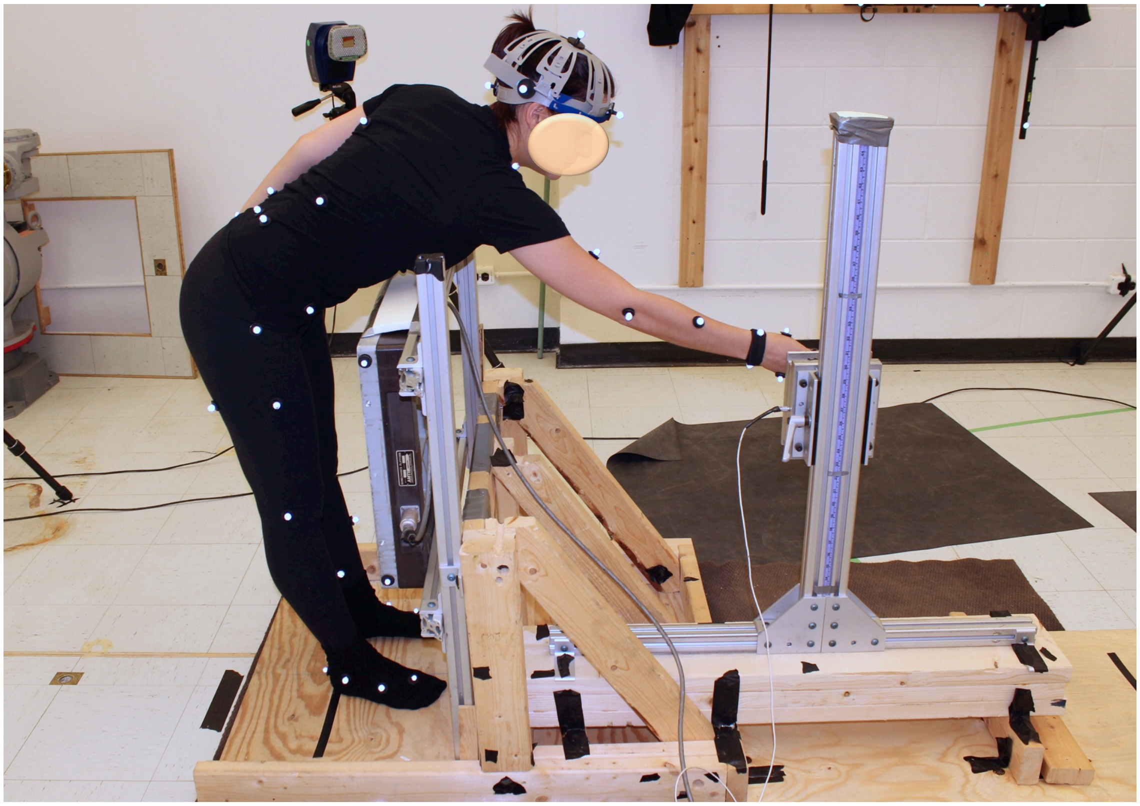


Figure 3.4: Participant performing a No Brace, Low-Far exertion standing in front of the bracing surface. Notice the 52 reflective markers placed on the landmarks stated in Table 3.2.

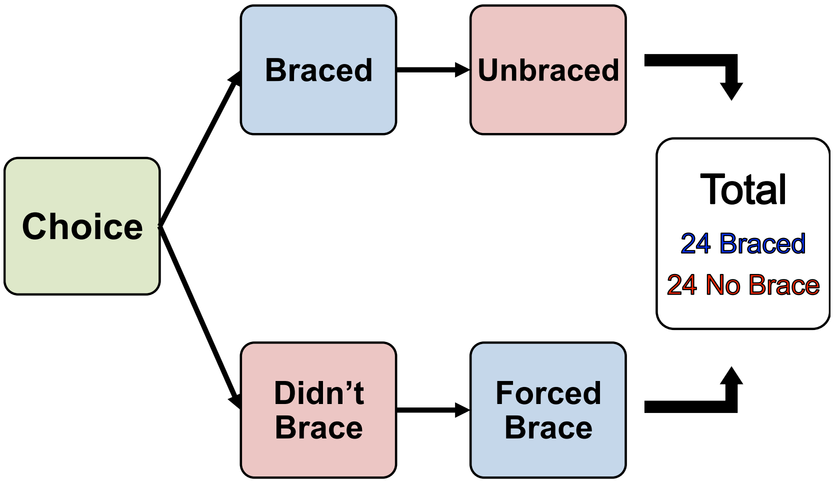


Figure 3.5: Schematic outlining the presentation of experimental trials. All 24 choice exertions were performed first, randomized blocked by Location. Trials

where bracing was chosen were performed without bracing surface. Trials where bracing was not chosen were performed with a Forced Brace.

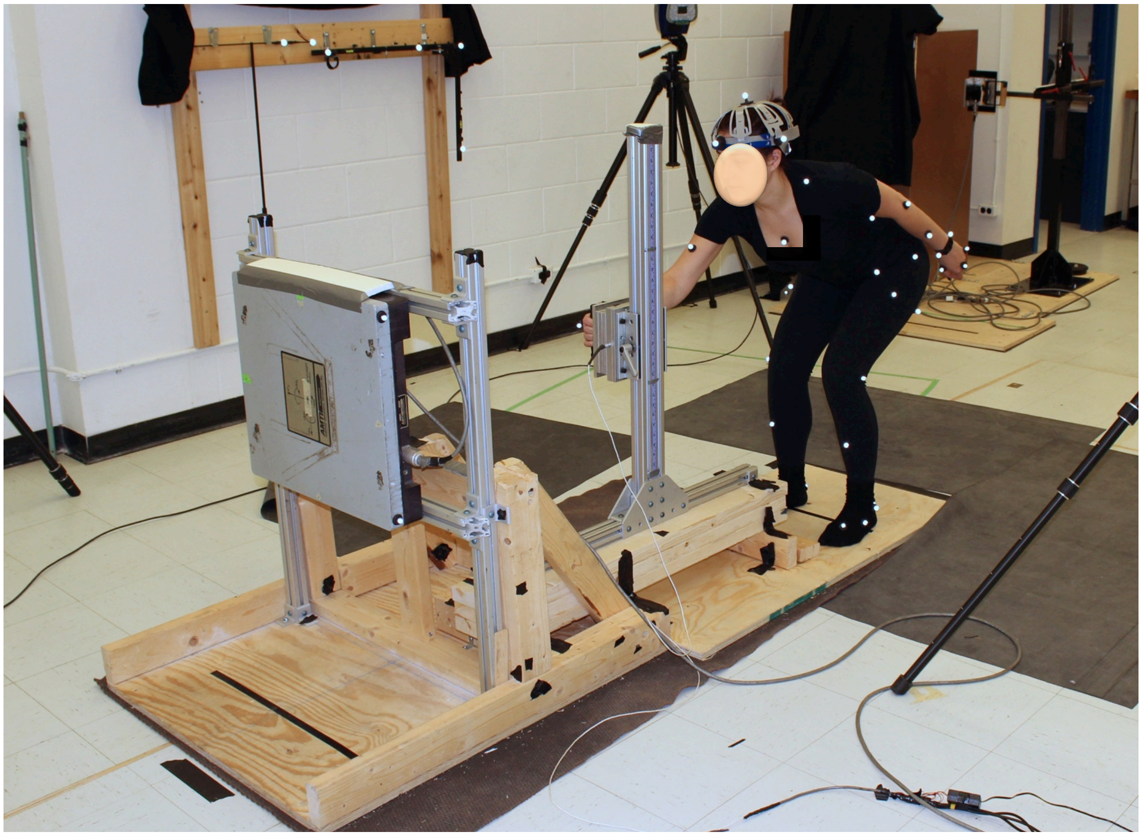


Figure 3.6: Participant performing a Low-Far exertion from the No Brace side of the apparatus.

3.3.3 – Standardized Strength Testing Protocol

Participants completed a standardized strength testing protocol using the Biodex isokinetic dynamometer. This was completed in a separate testing session from the experimental protocol. Prior to each test, the range of motion and 0° angle were set for the joint being tested so that correct positioning of the dynamometer was ensured. Limb weight was also calculated for shoulder and elbow tests. This session consisted of four separate strength tests. In each test, participants performed a 5-second ramped maximal exertion away from the body followed by a 30 second rest, then performed a 5-second ramped maximal exertion toward the body, followed by another 30 second rest. This was repeated such that four maximal efforts were recorded: two away exertions separated by 60 seconds of rest and two toward exertions separated by 30 seconds of rest. Peak torque (Nm) in each exertion direction was taken as the strength measure.

Maximal static isolated lumbar extension and flexion exertions were performed in a seated position at 60° of extension. Maximal static flexion and extension exertions of the right shoulder were performed at 60° of flexion in a seated position with the trunk braced (Figure 3.7, Left). Maximal static abduction and adduction exertions of the right shoulder were performed at 60° of abduction in a seated position with the trunk braced. Maximal static extension and flexion exertions of the right shoulder were performed at 90° of flexion in a seated position with the trunk and upper arm braced (Figure 3.7, Right). The participants exerted against the shoulder and elbow attachments with an inline power grip. Each attachment was adjusted according to manufacturer's specifications for each individual and the dynamometer head was positioned at the joint center of rotation.

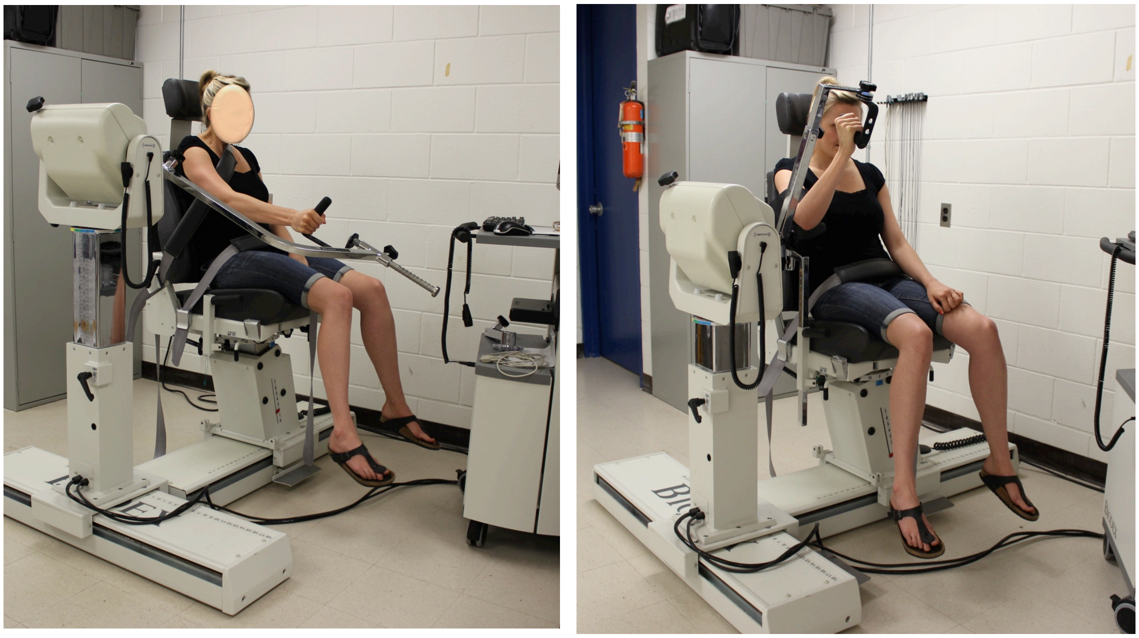


Figure 3.7: *Left*—Maximal seated shoulder flexion/extension test at 60° of extension. *Right*—Maximal seated elbow flexion/extension test at 90° of flexion.

3.4 – Data Analysis

A static posture was analyzed for one trial for each condition performed by each subject. The posture that was analyzed was recorded at the instant when the force in the required Direction comprised at least 90% of the resultant force and the requested load magnitude of the trial was achieved, based on a one-second moving average. A female manikin with the same anthropometric characteristics as the participant was paired with the motion capture co-ordinates recorded for each trial. Using the Motion Analysis module in Jack, this process aligned the manikin's body parts to the skeletal segments calculated using the motion capture data. Once the manikin was in the posture, a force vector corresponding to the trial exertion was applied at the task hand (Figure 3.8). The Static Strength Prediction (SSP) tool in Jack was used to output the following kinematic measures: elbow angle, vertical and horizontal shoulder angle, humeral rotation angle of the shoulder, and trunk flexion, lateral bend, and axial twist angle. In addition, Jack SSP was used to output the elbow flexion-extension moment, forward-backward rotation moment of the shoulder, abduction-adduction moment of the shoulder, humeral rotation moment of the shoulder, trunk flexion-extension moment, trunk lateral bend moment, and trunk axial twist moment.

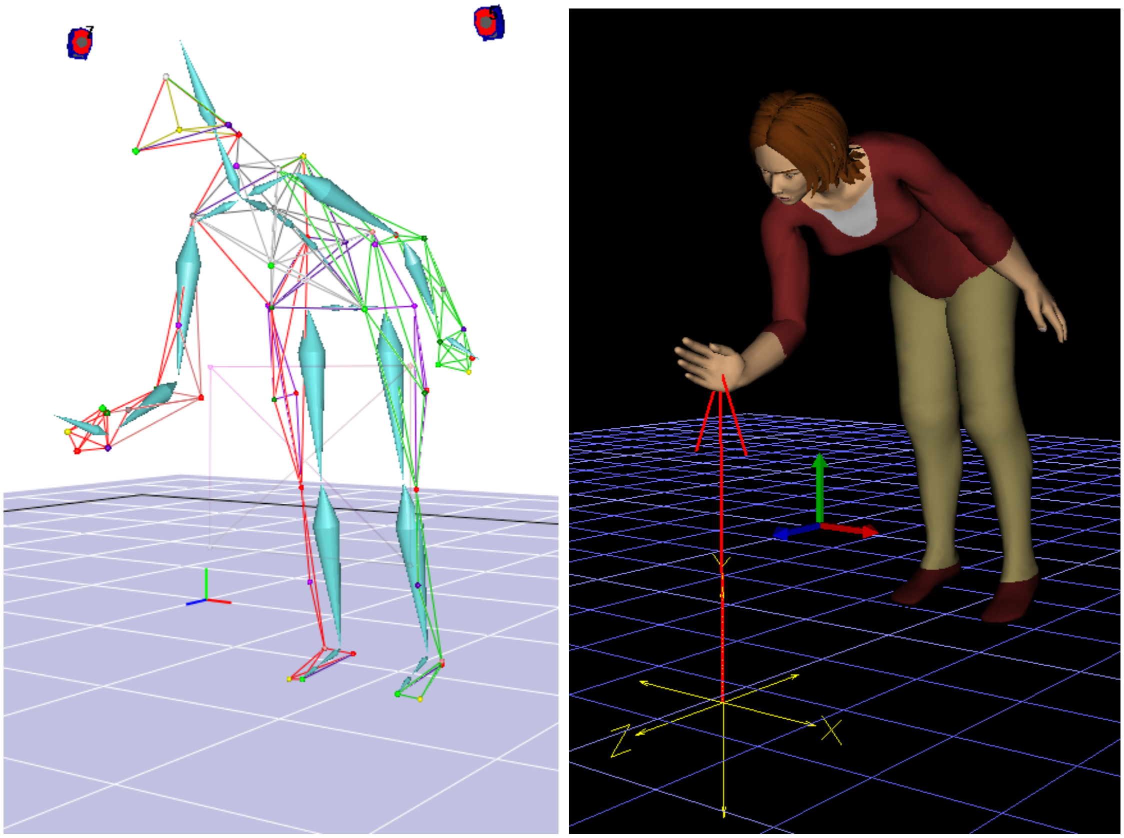


Figure 3.8—*Left*: Processed trial data in Cortex complete with 52 markers and 23 skeletal segments. *Right*: Jack female manikin paired with the posture shown on the left. Note the applied force vector shown in red indicating a Down exertion.

For braced trials, the force plate data recorded were filtered using a one-second moving average. The brace force data corresponding to the time point when the task hand force met the required Load of the trial was used for analysis. The force plate was oriented such that the positive x-axis was going to the left, the positive y-axis was in the upward direction, and the positive z-axis was forward. The brace force used for statistical analysis was the resultant magnitude of the F_X, F_Y, and F_Z forces. The location of body bracing was determined using the vertical displacement of the center of pressure (CoP) applied by the bracing body part from the center of the force plate. The vertical displacement was obtained by dividing the moment created about the y-axis by the force measured in the z-axis. The center of the force plate was 23.5 cm below 0.5H for each participant. The value of the vertical CoP displacement was added to the absolute height of the center of the force plate and then divided by the participant's height. The measure of brace height was therefore expressed as a percentage of the participant's height. The brace force angle was calculated by taking the dot product of the resultant brace force vector with a unit vector in the forward direction (z-axis). The resulting angle represented the angle of the brace force away from a force directly forward into the plate. For choice conditions, trials where the participant did not brace were coded with a 0 and trials where participants did brace were coded with a 1.

3.5 – Statistical Analysis

3.5.1 – Statistical Analysis of Bracing Characteristics

For dependent variables: 1) brace choice, 2) brace force, 3) brace location, and 4) brace angle there was no Bracing IV. For these, the IVs were: 1) Location (n=4), 2) Load (n=2), and 3) Direction (n=3). A 4x3x2 repeated measures analysis of variance (ANOVA) was conducted for each of the dependent bracing variables. Tukey's post hoc analyses were conducted to test main and interaction effects.

3.5.2 – Statistical Analysis of Kinematic and Kinetic Variables

For the remaining kinematic and kinetic variables, the IVs were: 1) Location (n=4), 2) Load (n=2), 3) Direction (n=3), and 4) Brace condition (n=2). The dependent variables were: 1) right elbow angle, 2) resultant right shoulder angle (resultant of the vertical and horizontal angles), 3) trunk flexion angle, 4) trunk lateral bend angle, 5) trunk axial twist angle, 6) right elbow flexion/extension moment, 7) resultant right shoulder angle (resultant of the forward-backward rotation moment, abduction-adduction moment, humeral rotation moment), and 8) resultant trunk moment (resultant of the flexion-extension moment, lateral bend moment, axial twist moment). A 4x3x3x2 repeated measures analysis of variance (ANOVA) was conducted for each of the dependent kinematic and kinetic variables. Tukey's post hoc analyses were conducted to test main and interaction effects.

3.5.3 – Logistic Regression

A logistic regression was conducted to predict whether or not participants would brace. The following variables were entered into the regression: participant height, arm length, and mass, task hand height, reach, direction, and load, and strength measures of the shoulder (flexion, extension, abduction, adduction), elbow (flexion, extension), and trunk (flexion, extension).

CHAPTER 4 – RESULTS

Main effects and interactions were considered significant if both the p-value was less than 0.05 and the ω^2 indicated that the effect accounted for more than 1% of the total variance (Keppel and Wickens, 2004). All significant main effects and interactions for the bracing variables are presented (Table 4.1). Since the focus of this thesis was bracing, the main purpose of independent variables such as Location, Direction, and Load was to create a perturbation that would alter whether a Brace or No Brace response would result. For this reason, only significant main effects and interactions that involve bracing will be presented for the ANOVAs with a kinetic or kinematic dependent variable (Table 4.2).

Table 4.1: List of p-values of each effect tested for the bracing characteristic dependent variables. P-values are listed in the table and the ω^2 values are shown in brackets. P-values<0.05 are presented in bold-face type. If the ω^2 accounted for more than 1% of the variance, the values are shown in red. The highest-level significant effects for each independent variable that will be discussed in this chapter are highlighted in yellow.

Effect	**Brace Choice**	**Brace Force**	**Brace Height**	**Brace Angle**
Location (Loc)	**0.0001 (0.872)**	**0.0001 (0.259)**	**0.0001 (0.738)**	**0.0109 (0.159)**
Direction (Dir)	**0.0289 (0.025)**	**0.0001 (0.586)**	**0.0067 (0.051)**	**0.0001 (0.622)**
Load	0.0566 (0.003)	**0.0085 (0.019)**	0.2864 (0.000)	0.6495 (0.000)
Loc* Dir	0.7426 (0.000)	**0.0015 (0.022)**	**0.0091 (0.043)**	**0.0345 (0.029)**
Loc* Load	**0.001 (0.014)**	**0.0205 (0.009)**	0.524 (0.000)	**0.041 (0.007)**
Dir*Load	0.1076 (0.006)	**0.0005 (0.043)**	0.2354 (0.000)	**0.0148 (0.024)**
Loc* Dir* Load	0.9718 (0.000)	0.3663 (0.001)	0.8452 (0.000)	0.2263 (0.009)

Table 4.2: List of p-values of each effect tested for the kinematic and kinetic dependent variables. P-values are listed in the table and the ω^2 values are shown in brackets. P-values<0.05 are presented in bold-face type. If the ω^2 also accounted for more than 1% of the variance, values are shown in red. The highest-level significant effects for each independent variable, that will be discussed in this chapter, are highlighted in yellow. Non-bracing effects are shown in grey and will not be discussed.

Effect	**Elbow Angle**	**Resultant Shoulder Angle**	**Trunk Flexion Angle**	**Trunk Lateral Bend Angle**	**Trunk Axial Twist Angle**	**Elbow Moment**	**Resultant Shoulder Moment**	**Resultant Trunk Moment**
Brace	**0.0012 (0.280)**	**0.0001 (0.153)**	0.1011 (0.013)	**0.0268 (0.089)**	**0.0002 (0.303)**	0.1622 (0.000)	**0.0072 (0.11)**	**0.0001 (0.016)**
Location (Loc)	0.0001 (0.491)	0.0001 (0.738)	0.0001 (0.878)	0.0001 (0.534)	0.0002 (0.236)	0.0271 (0.004)	0.0003 (0.033)	0.0001 (0.370)
Direction (Dir)	0.0001 (0.108)	0.0001 (0.011)	0.0001 (0.026)	0.0001 (0.065)	0.0018 (0.026)	0.0001 (0.632)	0.0001 (0.270)	0.0001 (0.378)
Load	0.0194 (0.003)	0.0735 (0.000)	0.0306 (0.000)	0.0191 (0.002)	0.0004 (0.007)	0.0001 (0.024)	0.11 (0.019)	0.0053 (0.007)
Brace* Loc	0.4003 (0.000)	**0.0001 (0.064)**	**0.0001 (0.043)**	**0.0001 (0.101)**	**0.0001 (0.288)**	0.4957 (0.000)	0.3488 (0.000)	**0.0273 (0.003)**
Brace* Dir	**0.0001 (0.015)**	**0.0007 (0.007)**	0.1408 (0.000)	**0.0001 (0.021)**	0.1835 (0.001)	0.1336 (0.002)	**0.0001 (0.134)**	**0.0013 (0.006)**
Brace* Load	0.4933 (0.000)	0.2084 (0.000)	0.113 (0.000)	0.1482 (0.001)	0.1483 (0.001)	0.4703 (0.000)	0.5949 (0.000)	0.2601 (0.000)
Loc* Dir	0.0004 (0.011)	0.4017 (0.000)	0.0625 (0.002)	0.0001 (0.025)	0.0001 (0.024)	0.0011 (0.009)	0.0001 (0.248)	0.0001 (0.016)
Loc* Load	0.2048 (0.001)	0.098 (0.001)	0.5417(0.000)	0.0201 (0.003)	0.3727 (0.000)	0.5595 (0.000)	0.6969 (0.000)	0.4011 (0.000)
Dir* Load	0.0349 (0.002)	0.1687 (0.000)	0.1272 (0.001)	0.1325 (0.001)	0.2021 (0.001)	0.0001 (0.288)	0.0008 (0.051)	0.0001 (0.165)
Brace* Loc* Dir	**0.0036 (0.009)**	**0.0024 (0.003)**	0.3699 (0.000)	**0.0038 (0.012)**	**0.0135 (0.011)**	**0.0279 (0.005)**	**0.0001 (0.054)**	**0.0026 (0.005)**
Brace* Loc* Load	0.0653 (0.001)	0.8217 (0.000)	0.7265 (0.000)	**0.0064 (0.005)**	0.491 (0.000)	0.4538 (0.000)	0.5074 (0.000)	0.1109 (0.001)
Brace* Dir* Load	0.8404 (0.000)	0.2636 (0.000)	0.4878 (0.000)	0.553 (0.000)	0.525 (0.000)	0.5454 (0.000)	0.2195 (0.002)	0.2016 (0.000)
Loc* Dir* Load	0.0572 (0.002)	0.4181 (0.000)	0.6681 (0.000)	0.1785 (0.002)	0.8988 (0.000)	0.096 (0.002)	0.0001 (0.075)	0.0009 (0.006)
Brace* Loc* Dir* Load	0.4636 (0.000)	0.4005 (0.000)	0.4676 (0.000)	0.6376 (0.000)	0.2372 (0.001)	0.0707 (0.002)	**0.0002 (0.022)**	0.0617 (0.002)

4.1 – Bracing Characteristics

4.1.1 – Brace Choice

There was also a main effect of Direction on brace choice ($p<0.05$). Participants were 18.0% more likely to brace for Up vs Down exertions (Figure 4.1).

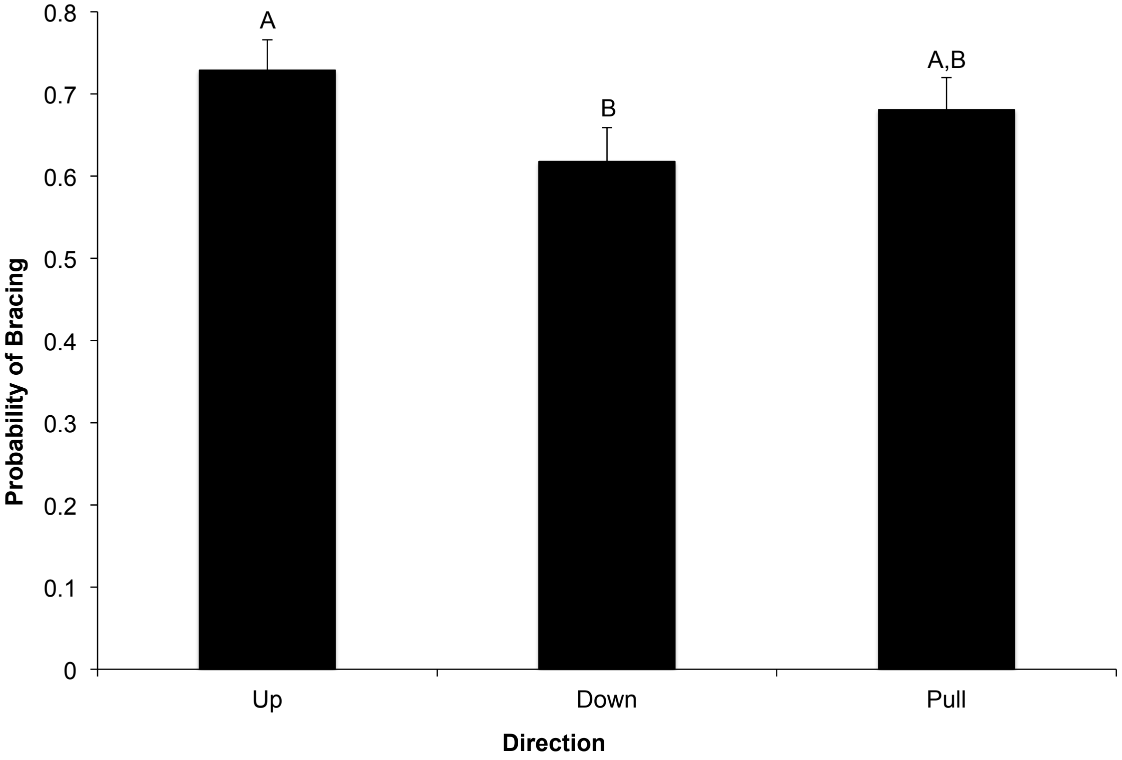


Figure 4.1: Main effect of Direction on the percentage of exertions where participants freely chose to brace. Mean and standard errors are shown (n=144). Means with different letters indicate significant differences.

There was a significant interaction effect between Location and Load (p<0.001). At the Low-Close task hand location, subjects chose to brace 37% more when exerting with a magnitude of 55 N compared to 27.5 N. There were no significant differences between load magnitudes at the remaining task hand locations (Figure 4.2).

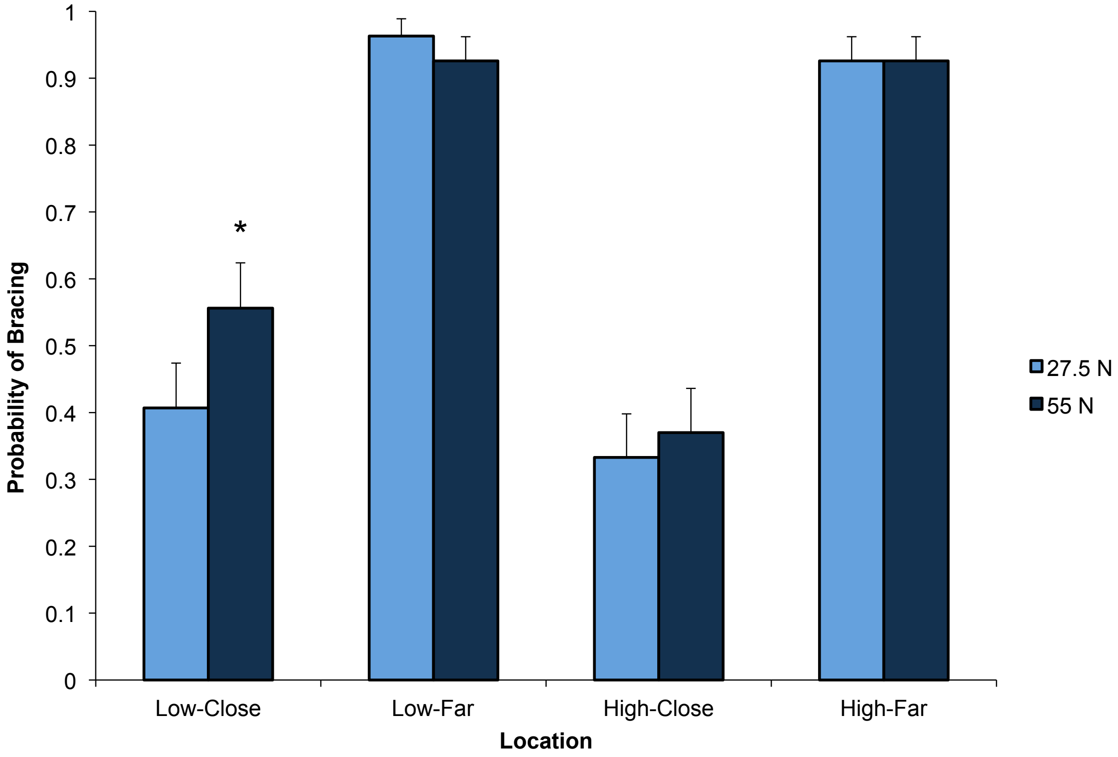


Figure 4.2: Interaction of task hand location and force magnitude on the percent of exertions where subjects voluntarily braced when given the option. Means and standard errors are shown (n=54). Significant differences between Loads are indicated by an asterisk.

4.1.2 – Resultant Brace Force

There was a significant interaction effect between Location and Direction ($p<0.01$) on resultant brace force. There were no differences between Low Locations for Up, however, these brace forces were higher than those at High-Far, which in turn is higher than High-Close. Down resulted in the same force production at both Low Locations, which were higher than both High Locations. There were no differences between Low Locations for Pull, however, High-Far was lower than Low-Close, but the same as Low-Far. All three of these Locations were higher than High-Close (Figure 4.3).

There was also a significant interaction effect between Direction and Load ($p<0.001$). The mean brace forces were 16% and 13% lower when exerting Up and Pulling, respectively for loads of 27.5 N compared to 55 N (Figure 4.4).

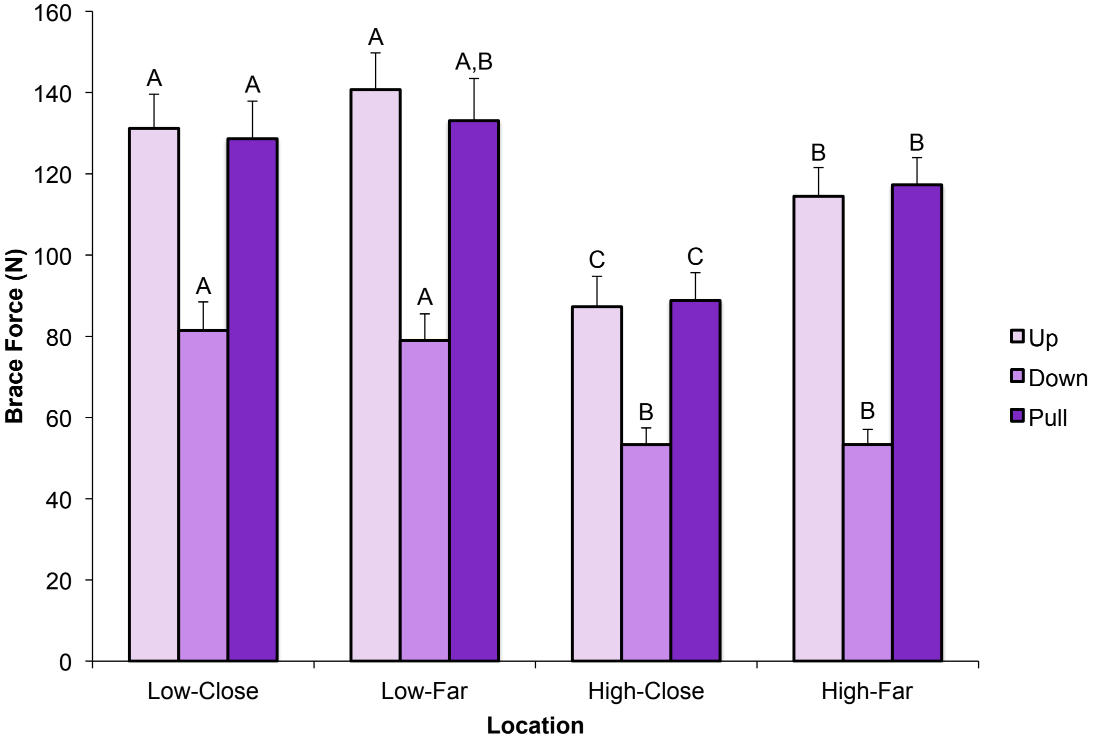


Figure 4.3: Interaction effect between Location and Direction on resultant brace force. Means and standard errors are shown (n=34). Significant differences in brace force between Directions are indicated by letters.

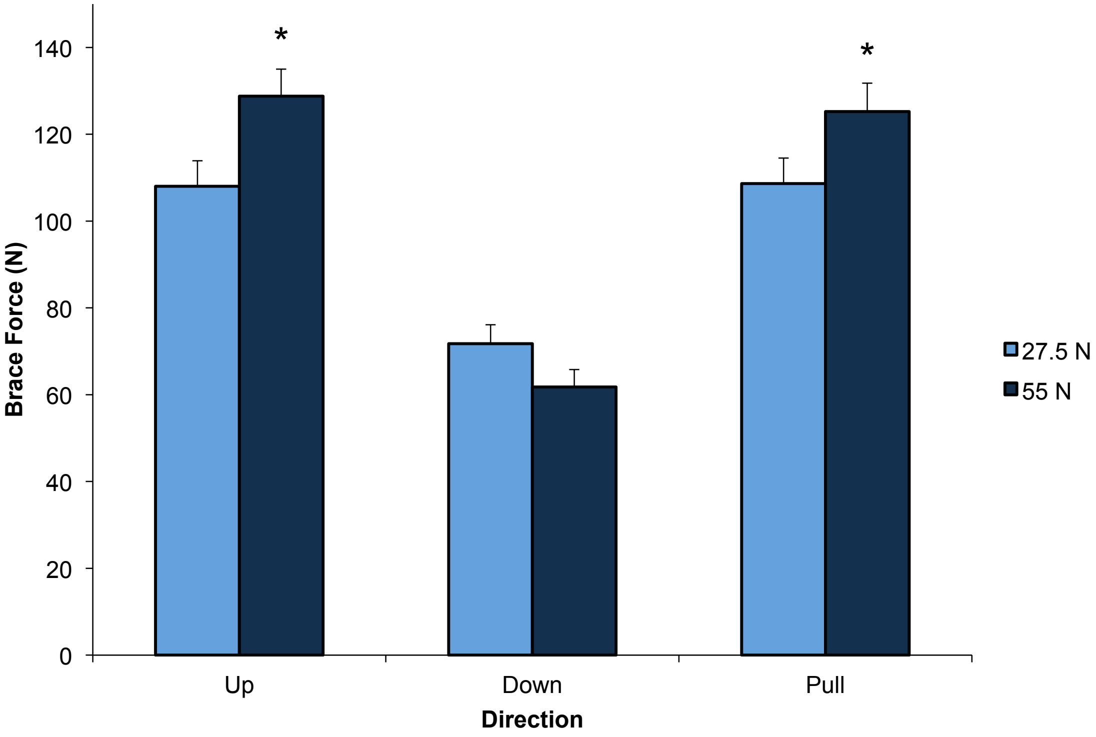


Figure 4.4: Interaction effect of Direction and Load on resultant brace force. Means and standard errors are shown (n=68). Significant differences between Loads are indicated by an asterisk.

4.1.3 – Brace Height

There was a significant interaction between Location and Direction ($p<0.01$) on the height of the center of pressure of the brace force. At the Low-Close Location, the brace height for Pull was 2.2% of stature lower than for Up. At the Low-Far Location, mean brace height was an average of 3.1% of stature higher when exerting Up compared to both the Down and Pull directions (Figure 4.5).

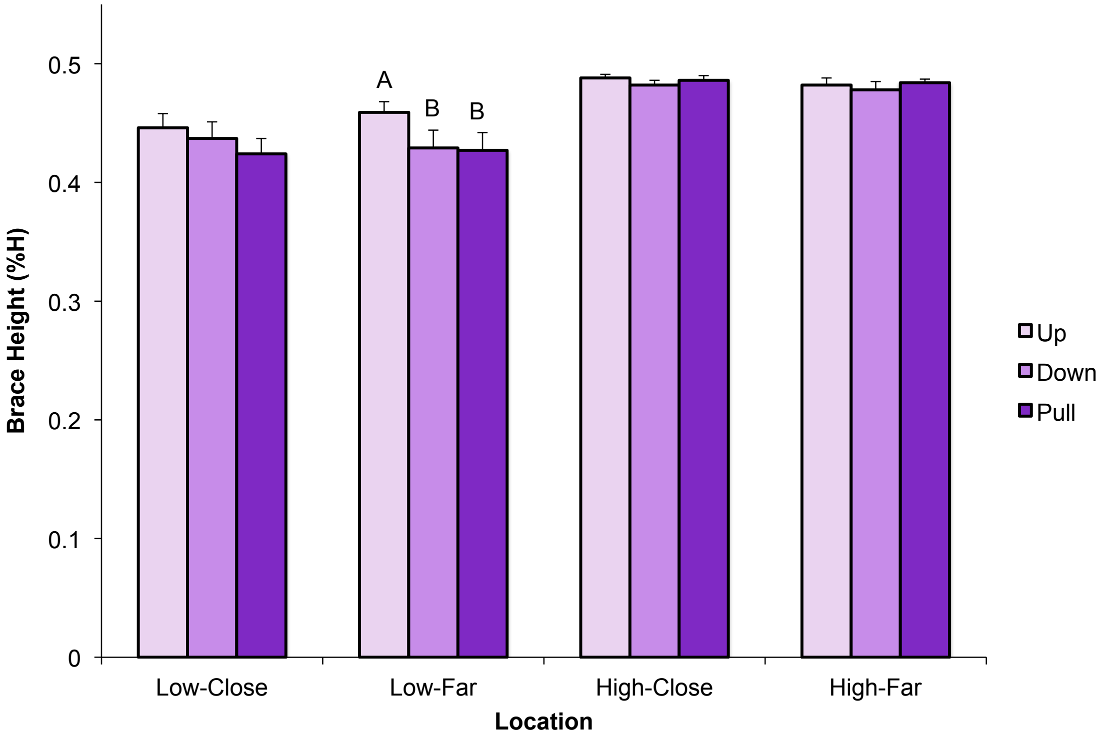


Figure 4.5: Interaction effect of Location and Direction on mean brace height as a percent of subject stature. Means and standard errors are shown (n=34). Significant differences between Locations are indicated by letters.

4.1.4 – Brace Force Angle

There was a significant interaction effect between Location and Direction on the angle of the resultant brace force ($p<0.05$). An angle of zero indicates that the force was acting directly forward into the force plate. Low-Close: exerting Down increased brace angle by 7.0° and 8.8° compared to Up and Pull, respectively. Low-Far: exerting Down increased brace angle by 6.5° and 8.7° compared to Up and Pull, respectively. High-Close: exerting Down increased brace angle by 4.4° and 5.8° compared to Up and Pull, respectively. High-Far: exerting Up and Down resulted in brace angles that were 4.6° and 6.9° higher than for Pull, respectively.

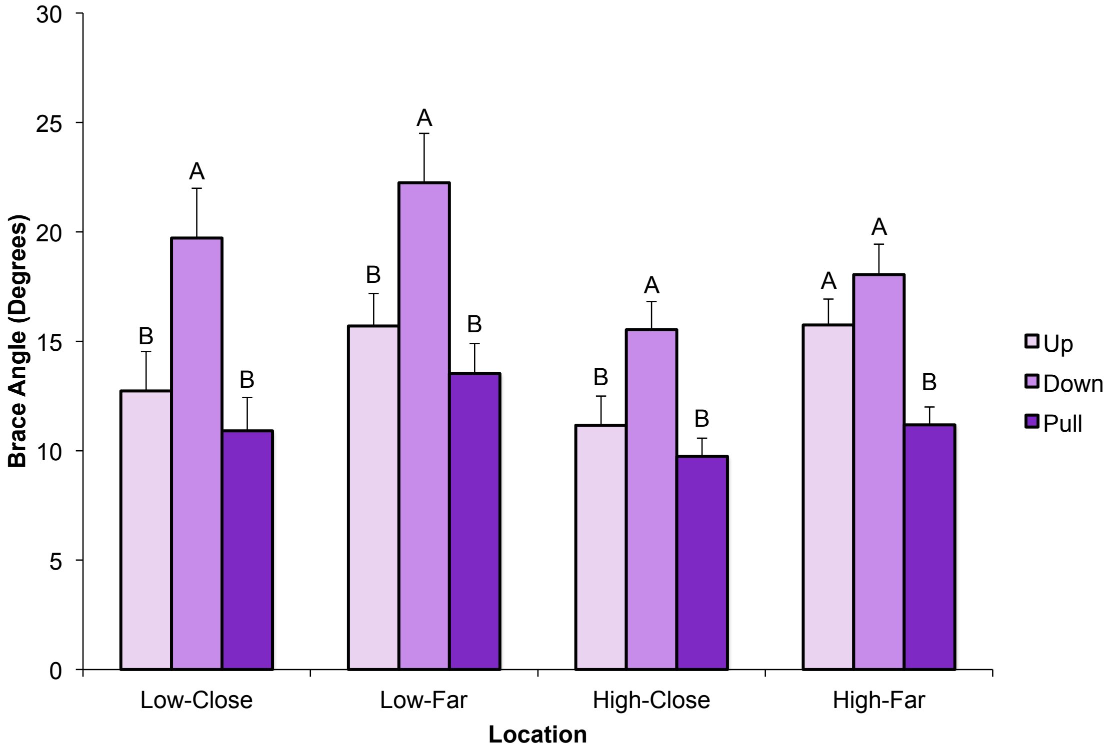


Figure 4.6: Interaction effect between Location and Direction on the resultant angle of the bracing force application. A zero angle indicates a force directly anterior into the force plate. Mean and standard errors are shown (n=36). Significant differences between Directions are indicated by letters.

There was also a significant interaction between Location and Direction on the angle of the resultant brace force ($p<0.05$). Brace angle became more deviated from directly anterior with a high Load when exerting Down, however it decreased with a high Load when Pulling (Figure 4.7).

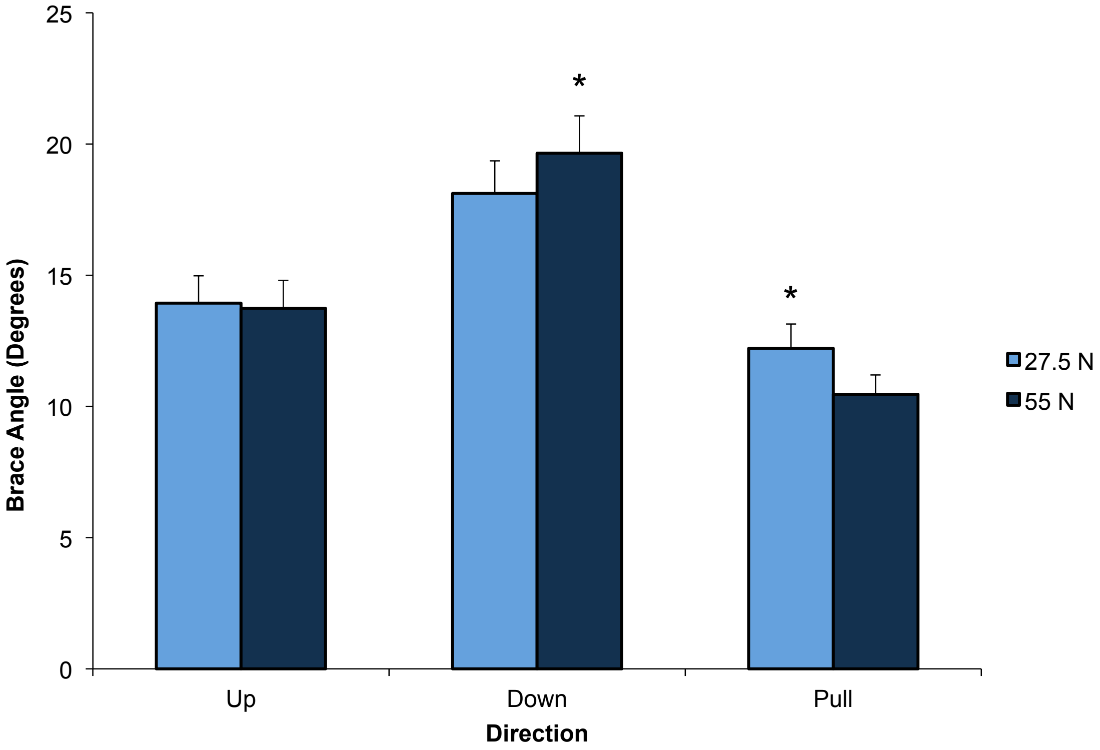


Figure 4.7: Interaction effect between Load and Direction on the resultant angle of the bracing force application. Mean and standard errors are shown (n=36). Significant differences between Loads are indicated by an asterisk.

4.2 – Joint Kinematics

4.2.1 – Elbow Flexion Angle of the Task Arm

There was a significant interaction between Bracing and Direction (p<0.0001). The Brace mean elbow angles were higher than with no bracing for all exertion directions. The greatest difference (19°) occurred when Pulling (Figure 4.8).

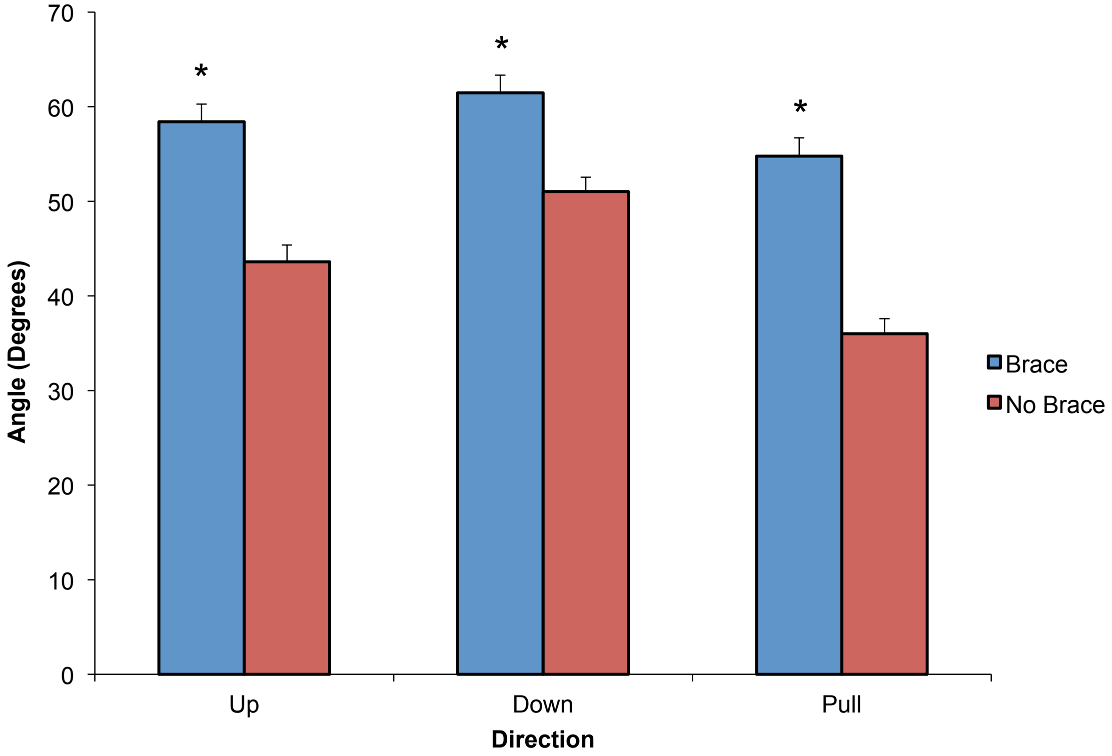


Figure 4.8: Right elbow flexion angle interaction between bracing and direction. Means and standard errors are shown (n=432). Significant differences between bracing conditions are indicated by an asterisk.

4.2.2 – Resultant Shoulder Angle of the Task Arm

There was a significant interaction effect between Bracing and Location for the resultant shoulder angle of the task arm (p<0.001). The No Brace angles were higher than when Braced at all task hand locations except for High-Close. The largest difference occurred at the Low-Far location, where the No Brace shoulder angle was an average of 20.8° higher (Figure 4.9).

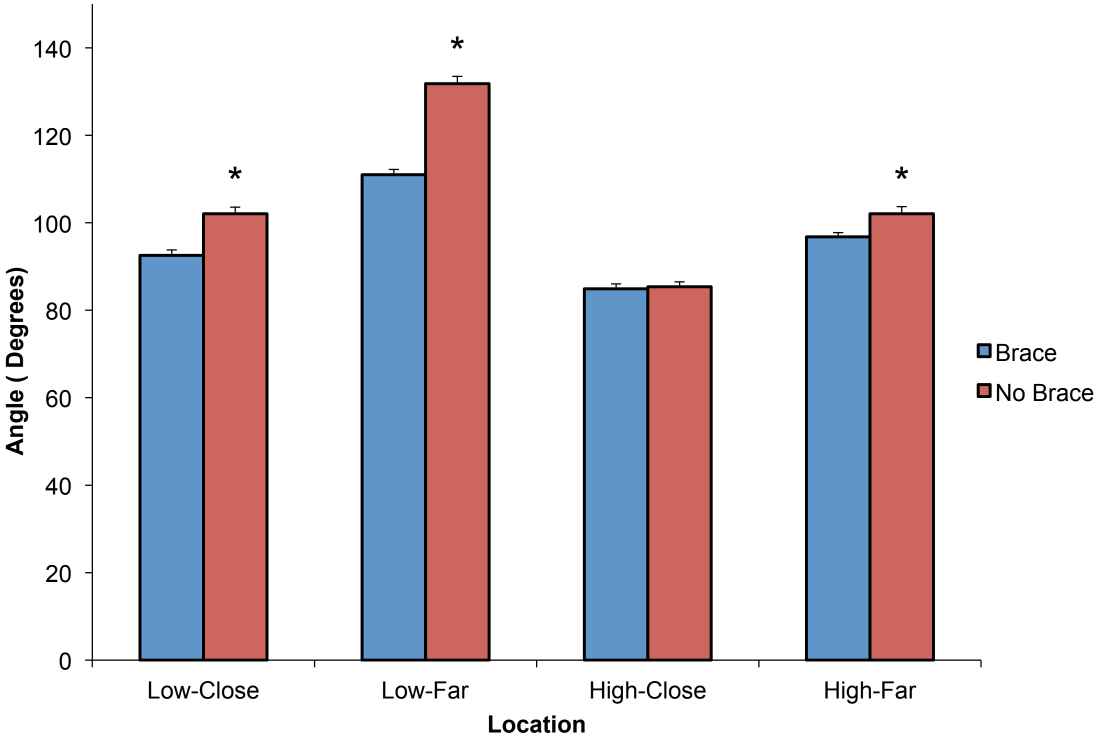


Figure 4.9: Interaction effect between Bracing and Location for resultant shoulder angle of the task arm. Means and standard errors are shown (n=108). Significant differences between bracing conditions are indicated by an asterisk.

4.2.3 – Trunk Flexion Angle

There was a significant interaction between Bracing and Location for the trunk flexion angle (p<0.001). The Braced angles were significantly higher for both Low task hand locations (Figure 4.10). The largest difference occurred at the High-Far location, where the No Brace trunk flexion was an average of 21.8° higher.

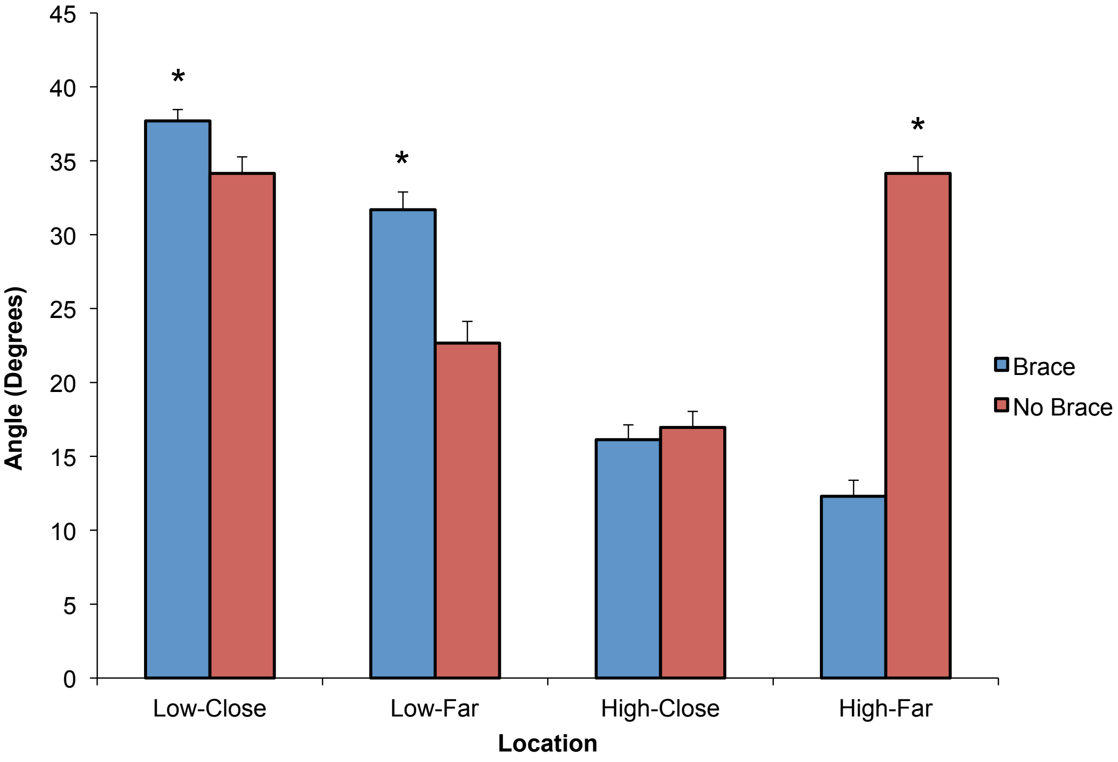


Figure 4.10: Interaction effect between Bracing and Location on mean trunk flexion angle. Means and standard errors are shown (n=102). Significant differences between bracing conditions are indicated by an asterisk.

4.2.4 – Trunk Lateral Bend Angle

There was a significant three-way interaction between Bracing, Location and Direction for the trunk lateral bend angle (p>0.01) (Figure 4.11). Post hocs were performed between each No Brace and Braced at each Location and for each Direction. Only significant differences will be noted.

Low-Close: When exerting Up, the No Brace lateral bend was an average of 3.6° higher than Braced. Low-Far: Bracing resulted in mean lateral bend decreases of 9.0, 3.3, and 6.3° during Up, Down, and Pull exertions, respectively, compared to No Brace conditions. High-Close: There were no differences in mean lateral bend between Brace and No Brace conditions for any of the exertion directions. High-Far: When exerting Up and Pulling there was a 2.6° and 2.9° reduction, respectively, in mean lateral bend in Brace conditions compared to No Brace conditions.

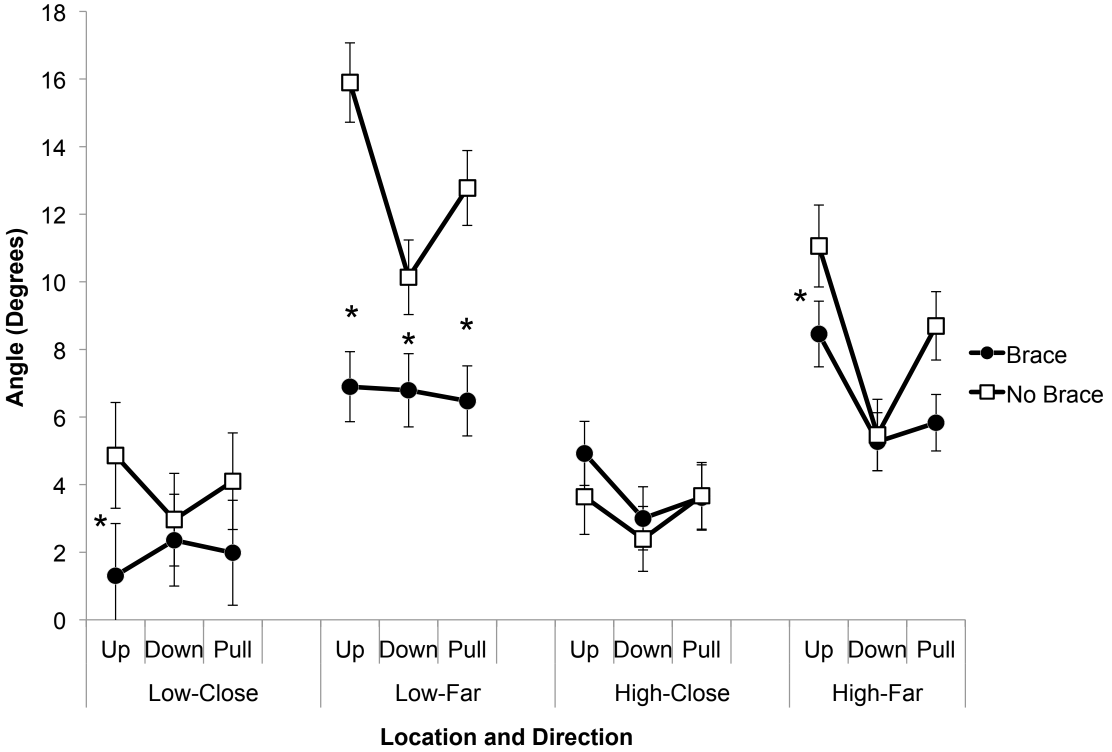


Figure 4.11: Interaction effect between Bracing, Location, and Direction on the trunk lateral bend angle. Positive angles indicate bending toward the right (task hand) side. Means and standard errors are shown (n=36). Significant differences between bracing conditions are indicated by an asterisk.

4.2.5 – Trunk Axial Twist Angle

There was a significant three-way interaction between Bracing, Location and Direction (p>0.05) (Figure 4.12). Only significant differences will be noted.

Low-Close: There were no differences in mean axial twist angle between Brace and No Brace conditions in any of the exertion directions. Low-Far: Bracing resulted in mean axial twist increases of 14.3, 9.2 and 11.6° during Up, Down, and Pull exertions, respectively, compared to No Brace conditions. High-Close: There were no differences in mean axial twist angle between Brace and No Brace conditions in any of the exertion directions. High-Far: Bracing resulted in mean axial twist increases of 8.2, 7.9 and 7.1° during Up, Down, and Pull exertions, respectively, compared to No Brace conditions.

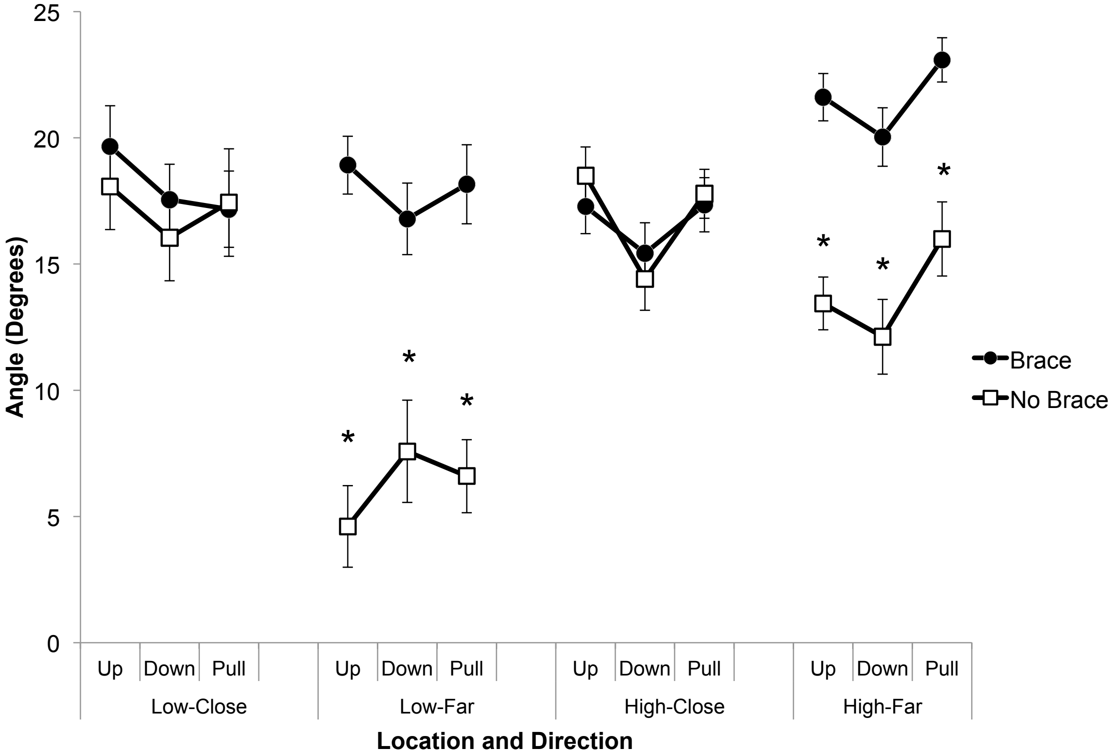


Figure 4.12: Interaction effect between Bracing, Location, and Direction on mean trunk axial twist angle. A positive angle indicates twisting toward the left side (task hand shoulder forward). Means and standard errors are shown (n=36). Significant differences between bracing conditions are indicated by an asterisk.

4.3 – Joint Kinetics

4.3.1 – Resultant Shoulder Moment at the Task Arm

There was a significant four-way interaction between Bracing, Location, Direction, and Load on the resultant shoulder moment at the task arm (p<0.001). The three-way interaction between Bracing, Location Direction is shown separately for Loads of 27.5 N (Figure 4.13 a) and 55 N (Figure 4.13 b). Only significant differences will be noted.

Load = 27.5 N

Low-Close: When exerting Down, there was a 44% reduction in mean shoulder moment for Braced compared to No Brace conditions. Low-Far: When exerting Up and Pull, there was a 43% reduction and 120% increase, respectively for Braced compared to No Brace conditions. High-Close: When exerting Up, there was a 39% reduction in mean shoulder moment for Braced compared to No Brace conditions. High-Far: No differences between Braced and No Brace conditions.

Load = 55 N

Low-Close: When exerting Up, there was a 36% reduction in mean shoulder moment during Brace conditions compared to No Brace conditions. Low-Far: When exerting Up and Pulling, there was a 46% reduction and 226% increase, respectively, in mean shoulder moment for Braced compared to No Brace conditions. High-Close: No differences between Braced and No Brace conditions. High-Far: When exerting Up, there was a 19% reduction in mean shoulder moment for Braced compared to No Brace conditions.

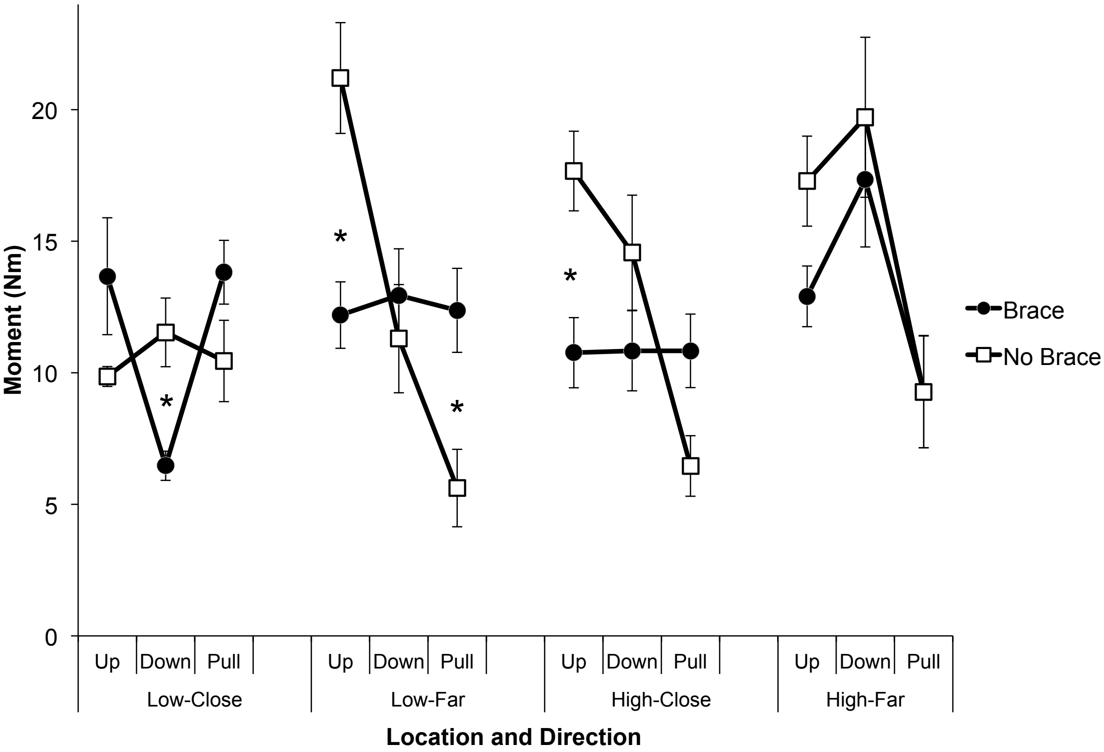


Figure 4.13 a) Interaction effect between Bracing, Location, and Direction on the resultant shoulder moment at the task arm for the 27.5 N exertion level. Means and standard errors are shown (n=18). Significant differences between bracing conditions are indicated by an asterisk.

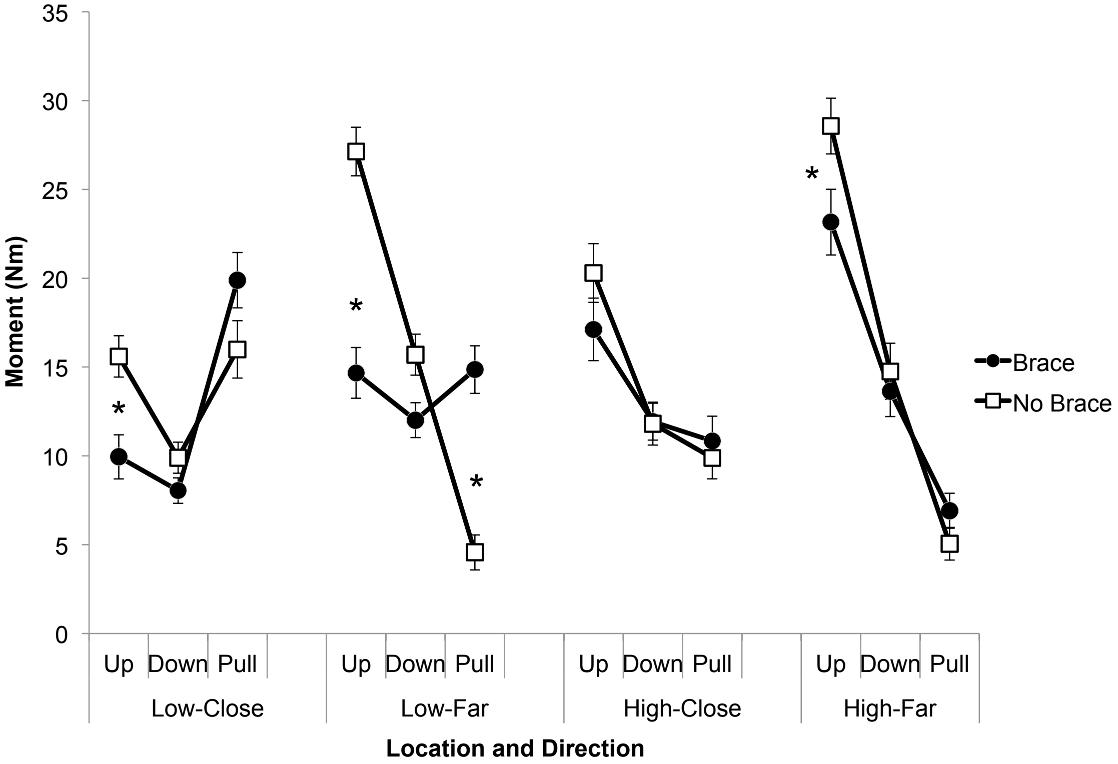


Figure 4.13 b) Interaction effect between Bracing, Location and Direction on the resultant shoulder moment at the task arm for the 55 N exertion level. Means and standard errors are shown (n=18). Significant differences between bracing conditions are indicated by an asterisk.

4.3.2 – Resultant Trunk Moment

There was a main effect of Bracing on resultant trunk moment (p<0.0001). Mean trunk moment decreased by 9% with the use of bracing (Figure 4.1).

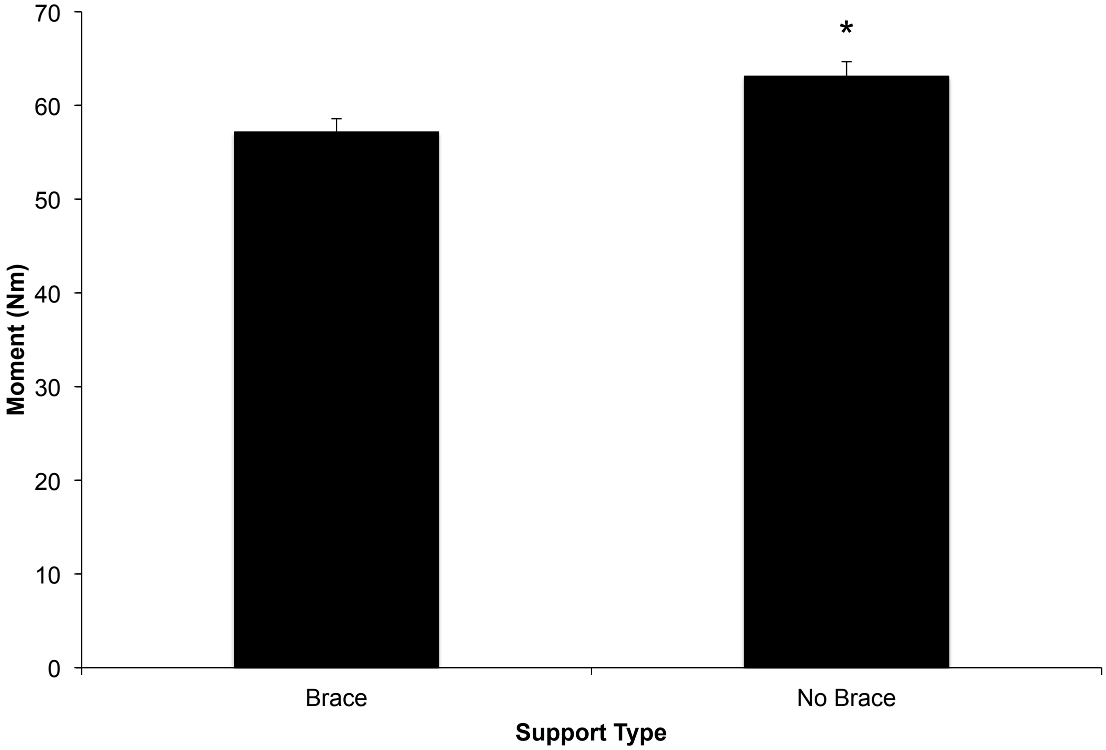


Figure 4.14: Main effect of Bracing on resultant trunk moment. Means and standard errors are shown (n=432). Significant differences between bracing conditions are indicated by an asterisk.

4.4 – Logistic Regression

The logistic regression analysis produced a model that explained 34.7% of the variance and correctly predicted the leaning behaviour in 79.8% of the 432 cases. The variables that were included in the regression were brace choice, participant height, arm length, and weight, task hand height, reach, Load, and Direction, shoulder flexion and extension strength, shoulder abduction and adduction strength, elbow flexion and extension strength, and trunk flexion and extension strength (Table 4.3). A 0 represented No Brace and a 1 represented Brace. Values less than 0.5 were rounded to 0 and values greater than 0.5 were rounded to 1.

Table 4.3: Logistic Regression summary for bracing prediction. Highlighted cells indicate variables with significant p-values < 0.05.

Logistic Summary Table for NB=0 Brace=1	
Count	432
# Missing	17
# Response Levels	2
# Fit Parameters	17
Log Likelihood	-177.763
Intercept Log Likelihood	-272.118
R Squared	**0.347**

Variable	Co-efficient	Std. Error	P-Value
Bracing Constant	-9.7182	3.8464	0.0115
Height	0.0081	0.0396	0.8385
Arm Length	-0.0313	0.0802	0.6961
Mass	-0.0376	0.0303	0.2152
TH Height (%H)	2.7751	1.3310	0.0371
TH Reach (%AL)	11.2807	1.1440	0.0001
Load	0.0101	0.0096	0.2927
Pull=1	0.0457	0.2796	0.8700
Up=1 Down=-1	0.4156	0.1640	0.0113
Shoulder Flex	0.0234	0.0330	0.4778
Shoulder Ext	-0.0507	0.0353	0.1505
Shoulder Abd	-0.0421	0.0208	0.043
Shoulder Add	0.0477	0.0225	0.0341
Elbow Ext	0.0157	0.0262	0.5495
Elbow Flex	0.0701	0.0347	0.0431
Trunk Ext	-0.0046	0.0034	0.1766
Trunk Flex	-0.0141	0.0085	0.0962

CHAPTER 5 – DISCUSSION

The most important finding of this study was that, when given the choice, participants were twice as likely to brace when performing a task with a far reach. In addition, average brace forces were approximately 117 N for Up and Pull exertions, and were nearly half that (67 N) for Down exertions. Bracing location tended to shift in accordance with task hand location, that is, participants would brace at a lower height at low versus high locations. Flexing the trunk forward and twisting the right shoulder forward, combined with a more flexed task arm and reduced shoulder rotation, allowed participants to adopt a posture where their shoulder was closer to the point of exertion during braced exertions.

5.1 – Bracing Characteristics

5.1.1 – Brace Choice

For the conditions tested, the choice to brace appeared to be dependent on the reach distance of the exertion. Pooled across load, participants chose to brace an average of 48%, 35%, 94%, and 93% in Low-Close, High-Close, Low-Far, and High-Far Locations, respectively (Figure 4.2). From this, a trend emerged where close and far locations were braced an average of 42% and 94% of exertions, respectively. The 30% increase in reach distance more than doubled the likelihood of participants choosing to brace. Since the far reach was set at a value greater than arm length (120%), the high incidence of bracing may indicate that external support was needed to maintain balance. In order to reach the task handle from a neutral stance, participants had to flex at the shoulder, extended at the elbow, and flex the trunk. This would shift the body's center of mass forward and increase the flexion moment on the trunk. The use of bracing allows the center of mass to be displaced forward by providing the necessary counter-moment to help reduce the moment on the trunk. Without bracing, the forward shift of the trunk and upper body would need to be offset by a rearward shift of the hips and increased flexion in the legs limbs. Another possibility is that the bracing surface provided a higher degree of postural constraint at these locations, eliciting a braced response simply because of the obstruction it provided.

There was an interaction between Location and Load for brace choice, but significant differences between Brace/No Brace were only found at the Low-Close Location, where increased Load increased the percentage of trials where bracing was freely chosen the first time a condition was presented (Figure 4.2). This suggests that the majority of the participants had the capability to exert the 27.5 N load without the use of external support. When the load was increased to 55 N, however, the need for bracing increased as well. Since the reach distance was quite extreme for Far locations, participants would choose to brace based simply on the task hand location, and not the Load. In High-Close, the task handle was located at waist-height and within an arm’s reach, a relatively neutral posture compared to those seen at the other Locations, and bracing was not necessary to complete the exertion. Thus, it makes sense that Load would only increase the probability of bracing at Low-Far.

5.1.2 – Brace Force

There was an interaction between Load and Direction on Brace Force. An increased load resulted in increased bracing forces for the Up and Pull directions, but had no effect on Down exertions (Figure 4.4). Exerting Up against the task handle exerts a downward reaction force on the hand, while pulling exerts a forward reaction force on the hand. These reaction forces create a moment that would tend to rotate the body forward, towards the bracing surface. An increased load at the task hand would result in an increased reaction force, and an increased moment with the tendency to rotate the body forward. This would likely account for the need for increased brace forces at the thighs. This is consistent with Jones (2011), who reported increased bracing force magnitudes with increased task hand exertion forces. She also reported the highest brace forces with Up and Pull exertions, as in this study, although Down was not measured by Jones (2011).

A novel feature of the current study is the investigation of bracing behaviours during Downward exertions. Down elicited a different behavioural response than both Up and Pull, in that participants chose to Brace less and would Brace with a lower force. The lowest Brace forces occurred during Down exertions, across all Locations (Figure 4.3) and there was no effect of Load on Brace force production during Down exertions (Figure 4.4). Exerting Down against the task handle produces an upward reaction force on the hand, creating a moment that will tend to rotate the body backward. Exerting Down essentially provides a means of external bracing at the task hand by providing a counter-moment to the moment created by the forward displacement of the center of mass during the exertion. Fischer et al. (2012) suggest that downward exertions are biomechanically limited by arm strength rather than balance. Since a counter-moment is provided at the task hand, no further support was likely needed from bracing.

5.1.3 – Brace Height

When pooled across Direction, the average height of the center of pressure of the bracing force occurred at 43% and 48% of stature for Low and High Locations, respectively (Figure 4.5). This corresponds to 70 cm and 78 cm on a 50th percentile female, which would be in the upper thigh area. Although knee angle was not tested in an ANOVA for this thesis, the lower bracing contact point was qualitatively observed as resulting from increased knee flexion, to get the body physically lower when performing the low exertions. There was an interaction between Direction and Location on brace height. At the Low-Far location, Up exertions had higher brace heights than both Down and Pull. In this location, participants would most likely use their legs and trunk to help create the Up force at the task hand. Straightening their knees and extending their trunk with a rigid arm would aid in producing the Up exertion while minimizing stress on the shoulder. With more extended knees, the bracing contact point would become higher.

The survey we conducted at Ford reported that 50 cm was the most common height of body bracing (Cappelletto et al., 2012). The heights used for bracing in this study were higher than this at all Locations. This may be due to the nature of the bracing surface we used. The bracing surface was flat, unlike the distinct curves found on a vehicle that may be used to brace upon during assembly tasks.

5.1.4 – Brace Force Angle

The brace force angle represented the rotation of the resultant bracing force away from a horizontal vector that was directly anterior, into the plate. There was an interaction between Location and Direction on brace angle (Figure 4.6). The brace angles for Down were significantly higher than for Pull at all Locations. There was also an interaction between Direction and Load on brace force angle. Brace angle increased when exerting Down at the high Load compared to the low Load. Brace angle, however, was decreased when Pulling at the high load compared to the low Load.

Pull had the smallest brace force angles across all locations which resulted from a greater forward component of the brace force compared to the downward component. Pulling exerts an opposing, forward reaction force on the hand that tends to rotate the body forward and into the bracing plate, resulting in a greater horizontal force component than vertical force component. This is consistent with the findings from Jones (2011) who proposed that the oppositional component of the brace force is used as a strategy to generate the force at the task hand while also increasing the functional base of support.

Additionally, this theory would explain why brace angle decreased when Load was increased, as participants would have needed the increased oppositional force component at the bracing point of contact to help produce the necessary Pull force at the task hand.

5.2 – Biomechanical Benefits of Bracing

5.2.1 – Posture

5.2.1.1 – Trunk Posture

There was increased trunk flexion at the Low Locations with Bracing, yet decreased flexion at High-Far (Figure 4.10). Axial twist increased across all Directions at the Far Locations (Figure 4.12). The rotation of the right shoulder forward toward the task handle, combined with increased trunk flexion at the Low locations, allowed participants to essentially increase their functional arm length by moving their shoulder closer to the task handle. This increase in functional arm length is consistent with the findings of Damecour et al. (2010). Trunk flexion was significantly increased at High-Far in the No Brace condition. Because there was no external support to help maintain balance, participants would need to flex their trunk in order to reach the handle as well as shift their pelvis posteriorly to counter the forward shift of their center of mass.

There was an interaction between Location and Direction on lateral bend angle of the trunk (Figure 4.11). Lateral bend was significantly decreased in Up exertions at all Locations except for High-Close. Exerting Up produces a downward reaction force at the task hand and the downward moment that would result likely necessitated lateral bending toward the task side. Bracing, however, provided a support point with a counter moment to help maintain a more upright trunk posture in the frontal plane. Lateral bend was also significantly decreased for Pull exertions at the Far Locations. Pulling produces a reaction force that creates a moment with the tendency to rotate the body forward. This forward rotation would also tend create a lateral bend of the trunk on the task side. Bracing provides a backward counter-moment to this forward rotation that would, in turn, account for the reduction in lateral bend seen in Braced Pull trials.

5.2.1.2 – Shoulder Posture

The resultant shoulder angle, comprised of vertical (flexion) and horizontal (abduction) angles, was reduced when bracing at all locations except for High-Close (Figure 4.9). These reductions were the result of a decrease in the vertical shoulder angle (a less flexed shoulder) with the same amount of abduction. Since participants adjusted the position of their trunk so that their shoulder was closer to the task handle, the shoulder was able to be in a more neutral posture when bracing.

5.2.1.3 – Elbow Posture

As noted previous, bracing was associated with a shift in posture that allowed the participant to get closer to the task handle. Consequently, task arm elbow flexion increased for all three directions, when bracing versus no brace (Figure 4.8). Although the elbow was more flexed by an average of 15° with bracing, there was no effect of bracing on elbow moment. The flexed elbow allowed participants to get their body closer to the task handle, yet provided no biomechanical advantage at the elbow joint.

5.2.1.4 – Integrated Postural Findings

The upper body postural adaptations made during bracing exertions allowed participants to move their shoulder closer to the task handle by flexing the trunk, twisting the right shoulder forward, and flexing at the elbow, while keeping a more neutral shoulder posture. This is consistent with Hoffman (2008) who found that participants would alter the shoulder location of the task arm, relative to the task handle, as a means to reduce shoulder moment.

It is interesting to note some of the trends that occurred at the High-Close Location, which resulted in the most neutral posture of the four Locations. Bracing had no effect on shoulder, trunk flexion, lateral bend, or axial twist angles at this Location. Since participants were exerting at waist-level, and within arm's reach, bracing did not appear to be necessary to complete these exertions. This is also reflected in High-Close having the lowest incidence of Brace choice (35%) and the lowest bracing forces (76 N) when bracing was used (Figure 4.3). When forced to brace in this position, participants seemed to adopt similar task arm and trunk postures, as the unbraced counterpart exertions, but it was observed that they shifted the pelvis forward to contact the bracing surface with the thighs.

5.2.2 – Joint Moments

5.2.2.1 – Shoulder Moment: Task Arm

Resultant task shoulder moments across all trial conditions remained within the acceptable range for 75% of females. Resultant right shoulder moment was unique in that there was a significant 4-way interaction between the independent variables (Figure 4.13 a) and b)). Shoulder moment, when bracing, generally decreased, or did not change, for any combination of Direction, Location, and Load, when compared to No Brace conditions. The only exception was found at Low-Far, where the moments associated with pulling where substantially higher when bracing for both the 27.5 N and 55 N loads, despite the decrease in shoulder angle. The biomechanical mechanism for the reduction in shoulder moment in No Brace trials at Low-Far, Pull is unclear. This particular exertion needs to be investigated in more detail in the future. It is possible that the reduction in moment is the result of a modeling anomaly inherent in the Jack software.

5.2.2.1 – Trunk Moment

There was a main effect of bracing on resultant trunk moment (Figure 4.14). Trunk moment was significantly lower in Braced trials compared to No Brace trials. When collapsed across Location, Direction, and Load, trunk postures in No Brace trials had increased lateral bend and slightly larger flexion angles than Braced trials. Axial twist angle was lowered in No Brace exertions, however, axial twist would not affect the moment from the trunk mass. The combined effect of increased lateral bend and flexion angles in No Brace trials served to move the body's center of mass further away from a neutral position. By increasing the distance of the center of mass in No Brace trials compared to Braced trials, the lumbar moment created would be larger. Thus, the more upright trunk position seen in Braced trials resulted in a decreased moment. Jones (2011) did not measure trunk moments, yet speculated that trunk moment would decrease as a result of bracing. My thesis is novel in that it quantified the reduction in trunk moment associated with the use of external bracing at the thighs.

5.3 – Logistic Regression

The logistic regression resulted in an equation that was able to correctly predict bracing behaviours approximately 80% of the time (Table 4.3). Individual elbow, shoulder and trunk strength, as well as condition task Location and vertical exertion direction were significant predictors of bracing behaviour ($p<0.05$). From this, it can be concluded that bracing behaviour is dependent on both individual and task specific characteristics. Anecdotally, there were a few participants who chose to brace for the majority of trials. Typically, these individuals had joint strength measures that were below the population average. In terms of task-specific characteristics, participants chose to brace more if the task was at a far reach and at a low height. Further, an Up exertion was the more likely to elicit a braced response compared to the other exertion directions. These results support the findings of Fischer et al. (2012) who attributed having low arm strength, versus balance, to being a limiting factor when exerting Up or Down.

5.4 –Limitations

A limitation of this study is that the participants were university-aged females that were not experienced workers in automotive assembly tasks. The average age of an automotive assembly worker is increasing and this sample may not accurately reflect the strength capabilities or behaviours of that population. In addition, each trial exertion was only performed once. Automotive workers perform the same tasks multiple times a day. The learning effects that occur with repetitive work may result in different postural adaptation strategies and bracing behaviours.

The trunk flexion angle calculated by the Jack software is taken relative to a plane through the pelvis. This did not provide any information about how the trunk was oriented in relation to the brace plate, rather it provided a measure relative to a moveable part of the body. In a few cases, if a participant adopted a posture where their pelvis was rotated anteriorly, the trunk was reported as being in extension, even though the manikin appeared to be in a flexed position. In retrospect, it may have been more useful to take an absolute measure of trunk angle with respect to the vertical. This measure would indicate trunk flexion, yet allow for a better interpretation of how the trunk is oriented in a global reference frame.

The bracing surface was a force plate that was oriented vertically facing the participant, had foam padding on the superior border, and was adjusted to their individual height. In an automotive manufacturing plant, however, workers most often brace against the vehicle itself, which is usually curved (eg. fender).

The geometry of the different parts of the vehicle (i.e. bumper, fender, etc.) may dictate where a worker will brace simply because they protrude out from the vehicle itself. Further, the vehicle is in a fixed location at each workstation. The same part that is used for bracing may be around hip level for a 5th percentile female or around knee level for a 95th percentile male. The resulting postures of these two workers would differ greatly.

Whole-body marker set data were recorded for all experimental trials. In this thesis, however, only the postural variables of the task arm and trunk were presented. The elbow, shoulder, and trunk were specifically chosen for analysis because it was hypothesized that these body parts are where the greatest degree of postural adaptation would occur during braced exertions. These joints were also chosen for analysis because of the high prevalence of work-related musculoskeletal disorders in the upper extremity and at the low back. The postures and moments generated about the lower extremity were not analyzed. Currently, the proactive use of digital humans in ergonomics are unable to estimate joint moments below the point of bracing because of the unknown brace forces that create an indeterminate system. Examining the postures of, and forces on, the lower body may help to paint a better picture of the effect of bracing on the entire body. This, in turn, may enable the identification of which variable is most important for determining when a worker will brace, thereby enhancing the validity of predicting bracing behaviours.

5.5 – Applications

This study has many applications in the areas of ergonomics and work-related musculoskeletal disorder prevention. The primary application of this research is to aid ergonomists in accurately predicting if workers will brace during a task. If bracing will be used, this research will aid in predicting where a worker will brace and how much force will be used. If bracing behaviours will not be used, the no brace conditions provide information about the postural adaptations that occur during tasks with constrained reaches. Once there is a greater body of research in this area, these results can be used to identify the cognitive priorities placed on posture selection during tasks with external support and where the task environment is constrained. The ultimate goal of this work is to improve ergonomic analyses and reduce worker injury.

This thesis contributed to the understanding of bracing behaviours by addressing gaps in the literature. The following points summarize the impact of this research within the context of external support in the workplace.

1) Participants were able to choose whether or not they would brace during simulated automotive assembly tasks and the incidence of bracing in each task condition was documented.
2) Bracing behaviours, as well as postures and moments of the task arm and trunk, were analyzed for Down exertions. Jones (2011) did not include down exertions in her exploration of the effect of leaning and bracing on the capabilities of the task hand. The Cappelletto et al (2012) survey, however, indicated that Down was the second most common exertion direction used in automotive assembly tasks and was used in 22% of supported exertions.
3) Bracing forces during submaximal exertions were quantified and reported.

4) The Loads used in this study are representative of typical forces that would be used to complete various automotive assembly tasks.
5) A regression equation was developed that was able to predict whether or not bracing would be used with 80% accuracy ($r^2 = 0.35$).
6) Postures of the trunk and task arm were analyzed and adaptations made during Braced exertions and exertions with constrained reaches were identified.

CHAPTER 6 – FUTURE DIRECTIONS

This research has investigated how lower body bracing affects one-handed submaximal exertions. The following are suggestions for research, inspired by this thesis, that will expand upon its findings and may overcome certain limitations that were noted.

1. Provide a wider array of external support surfaces so that participants can choose whether leaning and/or bracing will be used. The survey at Ford indicated that 21% of supported exertions included a combination of leaning and bracing (Cappelletto et al., 2012). Having support surfaces for both leaning with the contralateral hand and lower body bracing, and allowing participants to choose their support type, will aid in the prediction of these behaviours in future ergonomic analyses.
2. Investigate how bracing behaviours change when performing one-handed vs. two-handed tasks.
3. Have participants perform braced and unbraced exertions while standing on a force plate so that the location of their whole-body center of pressure can be observed. Bracing allowed participants to shift their center of mass beyond the functional base of support. Quantifying the changes in center of mass location may aid in the prediction of bracing behaviours.
4. Consider factors in the cognitive process of posture selection. For example, does the perceived comfort of the bracing surface alter bracing behaviours?
5. Examine how the postural adaptation strategies used by skilled automotive workers differ from the sample population collected in this thesis.
6. Continue the postural analysis of the braced vs. unbraced postures collected in this study, including the lower limbs.

7. Incorporate the bracing forces collected in this study into existing musculoskeletal models so that joint moments below the point of bracing can be calculated.
8. Explore how bracing behaviours may be used as a means to offset fatigue during repetitive tasks.

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APPENDIX A

Letter of Information and Consent

An Investigation of Postures During One-Handed Submaximal Exertions with Extended Reaches

Investigators: Dr. James Potvin & Jessica Cappelletto

Principal Investigator:	Dr. James Potvin Department of Kinesiology McMaster University, Hamilton, Ontario, Canada **(905) 525-9140 ext. 23004**;
Student / Co-Investigator	Jessica Cappelletto Department of Kinesiology McMaster University, Hamilton, Ontario, Canada **(905) 525-9140 ext. 21327**;
Research Sponsor:	Automotive Partnership Canada

Purpose of the Study

The goal of this study will be to understand the postures and strategies that are adopted by humans during a one-handed task. This study will evaluate the whole-body postures adopted for four specific hand locations. It is hypothesized that whole-body postures and force generation strategies will change when there is an obstace present in the work environment. We believe that these obstacles may present an opportunity for external support using the thighs or hips. 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, and arm 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.

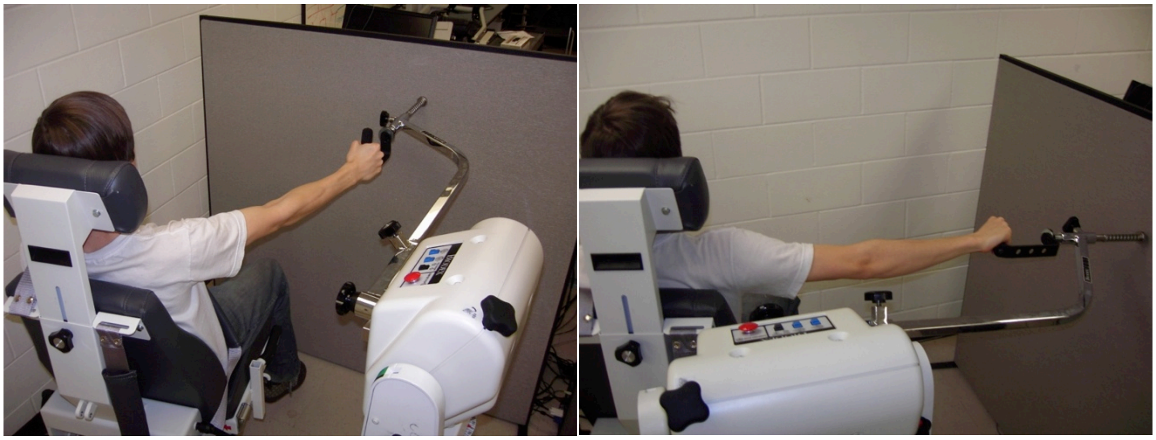
Kinematic sensors and motion capture cameras will be used to determine your posture while performing the exertions. Fifty-two infrared markers will be taped onto various parts of your body and will be tracked in 3-D space by infrared light reflection. These cameras will only emit and capture infrared 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. With your right hand, you will grip a padded handle that is mounted to a force plate. The force plate will be used to measure the force that you are exerting on the handle.

During the protocol, you will be asked to apply force on the handle attached to the force plate. You will exert against the handle in the required direction until you hear a tone. The tone will indicate that the desired force has been achieved. The handle will be set in four randomized positions. These positions are comprised of two heights (40% of height and 60% of height) as well as two reaches (90% of arm length and 120% of arm length). For each of the 4 hand locations, there will be 3 different exertion directions (pull back, exert upward, and exert downward). Each effort will last for 1-3 seconds. The task will be completed twice in each location and force direction, once in the presence of a bracing surface that may be used for external support, and once without the presence of the bracing surface. The choice will be up to you if you would like to use the bracing surface to help you complete the task when it is available.

In total, approximately 48 exertions will be completed during the study. In order to complete these exertions with adequate rest between trials, the entire protocol will occur in one two-hour testing session.

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 arm flexion/extension, adduction/abduction and trunk flexion/extension. During the strength testing protocols, your body will be secured. While seated in the Biodex, you will be asked to perform two 5-second maximum voluntary efforts (MVE) with one minute of rest in between, in each of the testing motions. During all of the MVE's you will be asked to push as hard as you can against the appropriate biodex attachment.



Potential Harms, Risks or Discomforts:
The conditions and trials will occur within a fairly short time frame, and participants may experience some mild fatigue in the arm but this should be no more than would be experienced after any unaccustomed physical activity. If you feel tired or experience any discomfort, you can take a break or stop the testing.

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

Payment or Reimbursement:
Participants will be reimbursed with a $5 Tim Horton’s gift card for each hour. The study will involve two data collection sessions, one for 120 minutes and one for 45 minutes.

Confidentiality:
You will be assigned a randomly generated subject code known only to the investigators, therefore 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 Jessica Cappelletto.

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

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

CONSENT

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

______________________	____________________	__________
Name of Participant	Signature	Date