

# **Determining the maximum feasible box dimensions and box masses for one-handed box transfers from varying heights**

by

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## **Author's Declaration**

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

## Abstract

**Background:** To address continued prevalence of musculoskeletal disorders (MSD) related to manual materials handling (MMH) in logistics and warehousing industries, more effort is being devoted to proactive ergonomics when (re)designing the workspace through the use of digital human models (DHM). However, effectively using a DHM requires the user to estimate how a worker will interact with an object. One example includes guessing when a worker might use one hand versus two when lifting and transferring a box. To avoid guessing we need a better understanding of the determinants for performing one-handed lifts and transfers to inform DHM users on when human-object interactions should be modeled with one-hand versus two.

**Purpose:** The aim of this work was to determine the maximum feasible box dimensions and masses that would permit a one-handed box lift and transfer from three shelf heights.

**Methods:** Two sex-balanced samples of 20 participants completed a series of box transfer tasks from varying shelf heights (ankle, greater trochanter (GT), shoulder height) to a table with their dominant hand. For Study One, participants were instructed to grab a minimally weighed retractable box from either front or top and expand/collapse its dimension until they perceived that they could no longer transfer it with only one hand. For Study Two, participants were instructed to grab the box from either front or top (using the maximum acceptable dimensions from Study One) and to adjust the mass of the box until they perceived that they could no longer transfer it with only one hand. Within-subject repeated measure ANOVA with an alpha value of 0.05 were used for both studies to detect for shelf height or grip orientation differences.

**Results:** The perceived maximum acceptable box width ranged from 70-73% of participant's hand length. Perceived maximum width decreased with higher shelf height when grasping the box from the top, while staying consistent when grabbing the box from the front regardless of shelf height. Perceived maximum mass was lower when grasping the box from the top regardless of shelf height and was lower when grasping the box from shoulder height compared to ankle height regardless of grip orientation.

**Discussion:** When the box width exceeded 124mm of the person's hand length and required more than 36.7% wrist strength, people may be more likely to use two hands. The discrepancy in perceived maximum acceptable box width and box mass when grasping from the top at shoulder height was potentially due to awkward hand/wrists posture or line of sight issues. The effects between grip orientation and shelf height on the perceived maximum lifting capacity for one-handed transfers should be considered when proactively designing stock-picking tasks to optimize safety. Additionally, an understanding of the maximum determinants helped set manual material handling limits for one-handed box transfers. Findings from the current investigations provided psychophysical insights into the one-handed lifting capacity of standard cardboard boxes with no handles.

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# Chapter 1: Introduction

Musculoskeletal disorders (MSD) associated with manual material handling (MMH) is an important societal problem to address. As reported to the Workplace Safety and Insurance Board (WSIB) in Ontario in 2023, lost-time injury claims have cost the Canadian economy approximately \$72 million, with MSDs being the leading type at over 40% (WSIB, 2024). Musculoskeletal disorders accounted for over 8 million outpatient physician visits made by 3.1 million adult Ontarians (28.5%) in 2013 (Power et al., 2022). Out of all the lost-time MSDs, overexertion associated with MMH was ranked the highest in terms of direct costs to employers with an average cost of \$12.84 billion per year, and awkward posture associated with MMH was ranked the 5<sup>th</sup> highest with an average direct cost of \$3.67 billion per year (Liberty Mutual, 2023). Not only do those types of injuries pose a significant and costly burden on WSIB, the health care system, and the province, but they also could be life-altering for workers themselves. MSDs have negative impacts on people's employment outcomes, regardless of their sex, age, occupational category, type of company, and comorbidities (Sérazin et al., 2013).

Ergonomics interventions can be made by employers to address MSD hazards either reactively or proactively. Reactive approaches that might include implementing engineering controls such as modifying existing equipment, purchasing new devices, and making changes to the workplace are deemed to be most effective as per the hierarchy of controls (CDC, 2023; Appendix A). However, reactive approaches may not be practically or financially feasible and it's possible that cost-effective proactive strategies can be considered to reduce MSD hazards during the work design stage. Proactive

ergonomics approaches allow problems to be identified and solved before injuries occur (White, 2015). Cost avoidance is not the only benefit of proactive ergonomics design, it is also associated with increased productivity and overall job satisfaction, with reduced worker turnover (White, 2015). Strategies like evaluating and redesigning workstations through digital human model (DHM) software are often used for proactive ergonomics.

DHMs enable proactive ergonomics by allowing a designer to simulate the impact of a proposed design by analyzing how a worker would perform a virtual work task, and then make changes to the task to reduce ergonomics risks before job implementation (White, 2015). Workers with different anthropometric characteristics performing manual tasks can be simulated in DHM software, allowing the job design to accommodate different populations. However, DHM has limited capability of predicting realistic and valid dynamic motions when the simulated work tasks involve human-object interactions that are not well understood (i.e., grasping object with one or both hands). Task goals and environmental constraints need to be determined before generating human motion prediction when using DHM, meaning that whether the avatar will use one hand or both hands is often pre-determined by the user, therefore the resulting prediction might not be biofidelic. Movement predictions are often based on mathematical operations of general statistical models with bound prediction power, especially when used on un-tested conditions or complex movement predictions (Zhang & Chaffin, 2005). Since psychophysical determinants or factors affecting the relationship between physical stimuli and subjective correlations were not considered, DHM users need to hypothesize on human behaviours and human-object interactions.

Understanding why people choose one MMH strategy over the other could drive more realistic DHMs for better proactive ergonomic work design. Certain MMH strategies like lifting and transferring a box with one-hand could result in higher biomechanical exposure and risk of developing MSD relative to two-handed transfers depending on the task, but if all lifts are simulated as two-handed, risks associated with one-handed lifts may be missed. Some evidence does exist to help us understand what task and personal characteristics might influence lift behaviours. It has been found that the mass, width, and origin of the objects could affect how people select movement strategies (Kingma et al., 2006; Liu et al., 2022; Tang et al., 2020). Grip orientation may also affect lifting capacity since it is associated with postural changes at the wrist (Mogk & Keir, 2003). Postures in which the hand/wrist is flexed, pronated and flexed, or  $> 7^\circ$  ulnar deviated would result in lower grip strength, since muscles crossing the wrist (i.e. flexor digitorum superficialis, flexor digitorum profundus, flexor pollicis longus) would not be in an optimal length to generate maximum force (Mogk & Keir, 2003; O'Driscoll et al., 1992; Winter, 2009). Individual characteristics like expertise in MMH and sex could also result in different movement patterns in MMH tasks (Marras et al., 2003; Plamondon et al., 2010, 2017). A more robust understanding of which factors most influence one- versus two-handed lifting behaviours is an important focus area within the broader problem of MMH-related MSD.

My research aimed to determine the maximum feasible box dimensions and massess that would permit a one-handed box lift and transfer from varying shelf heights. Secondly, my research aimed to determine how grip orientation may influence the maximum feasible box dimensions and masses when lifting and transferring a box with

one-hand. It was hypothesized that the maximum feasible box dimension and box mass would decrease with higher shelf heights or when grabbing the box from the top.

## **Chapter 2: Literature Review**

This chapter will begin with an overview of reactive and proactive ergonomics designs, followed by how digital human modeling enabled proactive ergonomics. Finally, potential determinants of one and two-handed MMH strategies will be discussed based on their biomechanical and psychophysical exposure.

### **2.1 Overview of reactive and proactive ergonomics design**

Traditional ergonomics assessments are often reactive. They are prompted by reported MSD injuries or complaints, and completed with human factor engineers (HFE) and health & safety specialists inspecting the existing work area to make recommendations for injury reduction (White, 2015). If there are financial and time-sensitive constraints, recommendations made under those conditions tend to be administrative controls like adding break time, training employees to modify their work techniques, and keeping their bodies in neutral postures as much as possible. Interventions relying on employee behaviour were approximately 5-20% effective, and interventions that aim to reduce exposure time were approximately 20-40% effective (Goggins et al., 2008). Despite being somewhat effective, those interventions can be challenging to sustain and manage over time (CDC, 2023). Engineering interventions like modifying existing equipment, purchasing new devices, and making changes to the workplace would be much more effective at over 40% but might not be practically or financially feasible (Goggins et al., 2008). Either way, resources need to be spent on both the ergonomics interventions and MSD claims when corrective measures are made too late with the reactive mindset of managing existing MSDs.

A comprehensive proactive ergonomics design would be beneficial for both employers and employees. From a cost avoidance perspective, MSDs tend to be preventable, treatable, and less expensive in the early stages. Once injuries occur, MSDs may be irreversible, and worker's compensation claims can be costly. Lost-time injury claims in Ontario alone have cost the Canadian economy approximately \$72 million over the year 2023 (WSIB, 2024). Cost avoidance is not the only benefit of a proactive ergonomics design, it is found that productivity can be increased by 10% to 15% when the designed job allows for neutral body posture, less force exertion, and motion (Martin, 2006). Additionally, because workers are more comfortable when work was designed with ergonomics principles, they will be less prone to fatigue, and therefore result in higher employee job satisfaction and reduced turnover (White, 2015). In general, a proactive ergonomic design can achieve multiple benefits when applied in the work design phase, which can positively and effectively influence the final setup of work configuration with minimal costs when more resources are available (White, 2015).

Despite numerous benefits, a lack of standardized design requirements makes it challenging for HFEs to apply proactive ergonomics work design in the real world. As suggested by Wulff et al. (1999), ergonomics requirement criteria should be “absolute, quantitative, short, precise, concise, concrete, specific, and clear” to reduce misinterpretations when applied by HFEs. This recommendation concurred with the respondents of an interview study of 5 Swedish companies, not only that ergonomics requirements should be set in the early stages of design phase, they also need to be explicit, understandable, applicable, verifiable, and objective (Falck & Rosenqvist, 2012).

## **2.2 Human motion prediction via digital human modeling (DHM)**

Understanding and predicting human motion is essential for proactive ergonomics design to create a safer workplace. The classic ergonomics model used in proactive ergonomics design is digital human modeling (DHM), which uses computational algorithms to predict the motion of a biomechanical representation of the human body. By designing a job with optimal predicted human-object interactions, early injury prevention for MSDs and critical events can be achieved (Xia et al., 2022). DHMs are commonly used in the upstream product or work design to simulate and obtain feedback regarding human performance, human systems integration, and human interaction to refine the design for injury prevention (Bataineh et al., 2016). There are two types of DHMs, one is data-based, and the other is physics-based. The data-based DHM constructs the biomechanical representation of the human body using previously collected motion data or existing anthropometric databases to predict human postures and motions (Zhang & Chaffin, 2005). The physics-based DHM uses mathematical models, like optimization-based models, to predict human postures and motions based on user-defined end targets (Xia et al., 2022). An optimization-based model is commonly used to address the kinematic redundancy of human motion, and is constructed with various performance criteria or cost functions to mathematically determine the best possible movement strategy that will result in optimized joint motion or muscle forces (Zhang & Chaffin, 2005). For all types of DHMs, the physical realism of the model will be determined by whether all degrees of freedom, axis of rotation, and body segment dimensions are correctly inputted (Zhang & Chaffin, 2005). However, DHMs are challenged when predicting realistic and valid dynamic motions where the simulated work tasks involve human-object interactions (i.e., grasping

objects with one or both hands). Since potential psychophysical determinants of MMH strategy selection are not well considered in DHMs, professional judgment is needed by the user to tell the DHM where an avatars hands, feet, or gaze might be when predicting a task behaviour (posture or motion). Cort & Devries (2019) found statistically significant differences in posturing strategies between the real human posture captured by a marker-based motion capture system and the predicted human posture obtained from Jack<sup>TM</sup> human motion simulation software during hand exertion tasks simulating automotive seat assembly, suggesting the need for a deeper understanding of how humans strategize their posturing techniques to improve practicality and bio-fidelity of DHMs.

### **2.3 Prevalence of one and two-handed MMH**

One and two-handed lifting behaviours are common in MMH work. In the cross-sectional survey study conducted by Tang et al. (2020) at 30 different manufacturing facilities in the United States, a total of 22874 lifting/lowering subtasks, 1359 tasks, and 713 jobs were observed. One-handed-only lifting accounted for a very small portion of lifts at each of the subtask, task, and job levels, while there was an increase in mixed-handed lifting when looking at task and job levels (Figure 1). However, because the exact proportion of one-handed lifting was not quantified in mixed-handed lifting, the use of one-handed lifting might have increased when looking at task and job levels, even though there was a decrease in one-handed-only lifting. Not only were manufacturing industries exposed to repetitive lifting, but it was also noted that workers in logistics industries are constantly exposed to repetitive motions of lifting and lowering loads (Gumasing & Casela, 2020). Despite the strong prevalence of one and two-handed lifting behaviours in different

industries, task or personal-related factors that drive decisions to use one or two hands while lifting are currently not well understood.

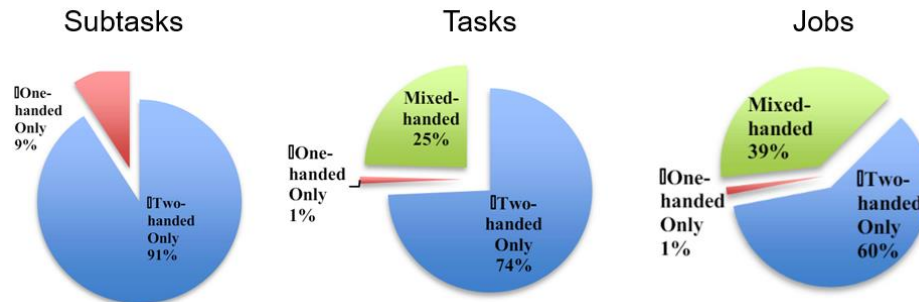


**Figure 1:** Figures from Tang et al. (2020) showing handedness of lifting/lowering at subtasks, tasks, and job levels across 30 different manufacturing facilities in the States.

## 2.4 Potential determinants of one and two-handed MMH

This subsection outlines potential determinants of one and two-handed MMH strategies based on their biomechanical and psychophysical exposures. A better understanding of why people move the way they do helps with proper work design, especially for jobs at distribution centers that are constantly exposed to MMH of different objects of different masses (Lavender et al., 2012).

### 2.4.1 Box mass

Load mass could be a potential work factor that leads people to prefer different MMH strategies. Tang et al. (2020) found that people tended to deal with heavier objects with both hands compared to only one hand (Table 1).

**Table 1:** Table from Tang et al. (2020) showing conditions when people chose one-handed lifting and two-handed lifting.

|                  | One-handed<br>N = 2097 | Two-handed<br>N = 20777 |                |
|------------------|------------------------|-------------------------|----------------|
|                  | Mean±SD                | Mean±SD                 | P value        |
| W (lb)           | 12.07±8.68             | 24.29±13.48             | < <b>0.001</b> |
| D (inch)         | 13.09±12.61            | 13.82±12.12             | <b>0.009</b>   |
| Max A (degree)   | 14.02±12.22            | 7.12±10.45              | < <b>0.001</b> |
| Max TF (degree)  | 27.74±22.66            | 33.93±27.54             | < <b>0.001</b> |
| Max TLB (degree) | 2.84±4.91              | 0.99±2.81               | < <b>0.001</b> |
| At origin        |                        |                         |                |
| H (inch)         | 19.17±5.63             | 17.59±4.85              | < <b>0.001</b> |
| V (inch)         | 36.53±11.67            | 35.51±12.21             | < <b>0.001</b> |
| TF (degree)      | 18.26±20.78            | 24.24±25.65             | < <b>0.001</b> |
| A (degree)       | 9.38±10.78             | 4.88±8.93               | < <b>0.001</b> |

*Note: W = weight; D = travel distance; A = trunk twisting; TF = trunk flexion; TLB = trunk lateral bending; H = horizontal distance between the object and the person; V = vertical distance between the object and the ground.*

Previous work has investigated the biomechanical exposures associated with one and two-handed carrying buckets. It was found that spine compression was higher when the same load was carried asymmetrically in one hand along with greater torso muscle activation to compensate for the reaction moment posed by the asymmetric load (McGill et al., 2013). Spine compression was further amplified with a heavier load when carrying in one hand (Figure 2). There was an increase in spine compression when participants were carrying load in one hand and than when carrying doubled load in both hands, indicating that two-handed carrying would be able to afford heavier loads (McGill et al., 2013). Because participants were upright walking, shear force remained relatively low throughout the trials (McGill et al., 2013).

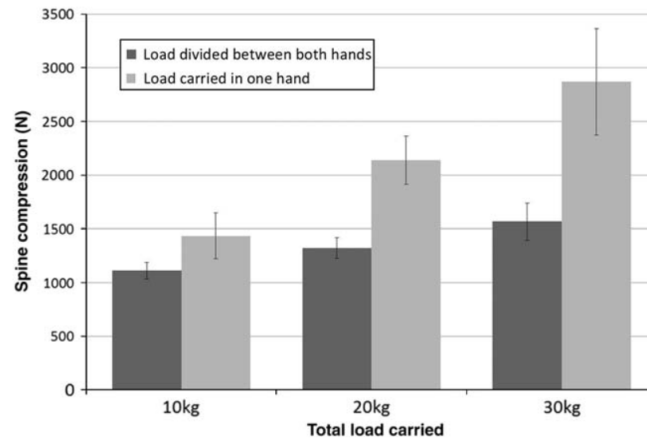


**Figure 2:** Figure from McGill et al. (2013) showing compressive load on the lumbar spine as a function of load carried in one or both hands.

On the other hand, Weston et al. (2020) found opposite results when comparing spinal compression in one and two-handed lifting/lowering tasks of 2.7 kg, 7.6 kg, 11.3 kg medicine balls with built-in handles on two opposite sides. When lifting the round medicine ball with one hand, the hand gripped the top of the ball directly. In contrast, when using two hands, the built-in side handles allowed the participants to place one hand on each side. It was found that peak compressive spinal loads were lower by an average of 7.4% when lifting with one hand and were lower by an average of 11.5% when lowering with one hand compared to both hands (Weston et al., 2020). Discrepancies were likely due to differences in the experimental setup. McGill et al. (2013) had participants carrying buckets (10kg, 20kg, 30kg) with their arms down at the sides, while Weston et al. (2020) had participants lifting medicine balls from ankle, knee, or waist heights. Both load mass and distribution of mass away from the participant's center of mass were different in the two studies, which led to discrepancies in spine load estimation. As a result, changing load mass and distribution would affect biomechanical exposure and this influence on

biomechanical exposure might affect one versus two-handed lifting decisions. Other than spine compression, Weston et al. (2020) also looked into peak lateral shear loads, it was found that peak lateral shear loads were higher by an average of 22.7% when lifting with one hand and were higher by an average of 12.4% when lowering with one hand compared to both hands, likely due to asymmetrical motion (Weston et al., 2020). Despite the increase in lateral shear loads, one-handed lifting was still prevalent in industries as found by Tang et al. (2020), indicating there would be other factors affecting the decision-making process of one versus two-handed lifting.

Psychophysical exposure was higher for two-handed MMH than one-handed MMH. In the study conducted by Yoon & Smith (1999), ten male participants completed a combination of lifting, carrying, and lowering activities with either one or both hands at different frequencies, while their self-perceived maximum acceptable masses, heart rate, ratings of perceived exertion (RPE), and time to complete each MMH task were collected. Even though the interaction effect between handling frequency and number of hands was not significant on RPE, there were significant interaction effects on maximum acceptable mass, heart rate, and tasking time (Yoon & Smith, 1999). The self-perceived maximum acceptable mass was described as the mass that participants perceived that they could handle comfortably for the task for a 1-hr period (Yoon & Smith, 1999). As can be seen from Figure 3, participants' perceived maximum acceptable masses or task capacity were higher when completing tasks with both hands, indicating that load mass could be a possible determinant for one and two-handed MMH.

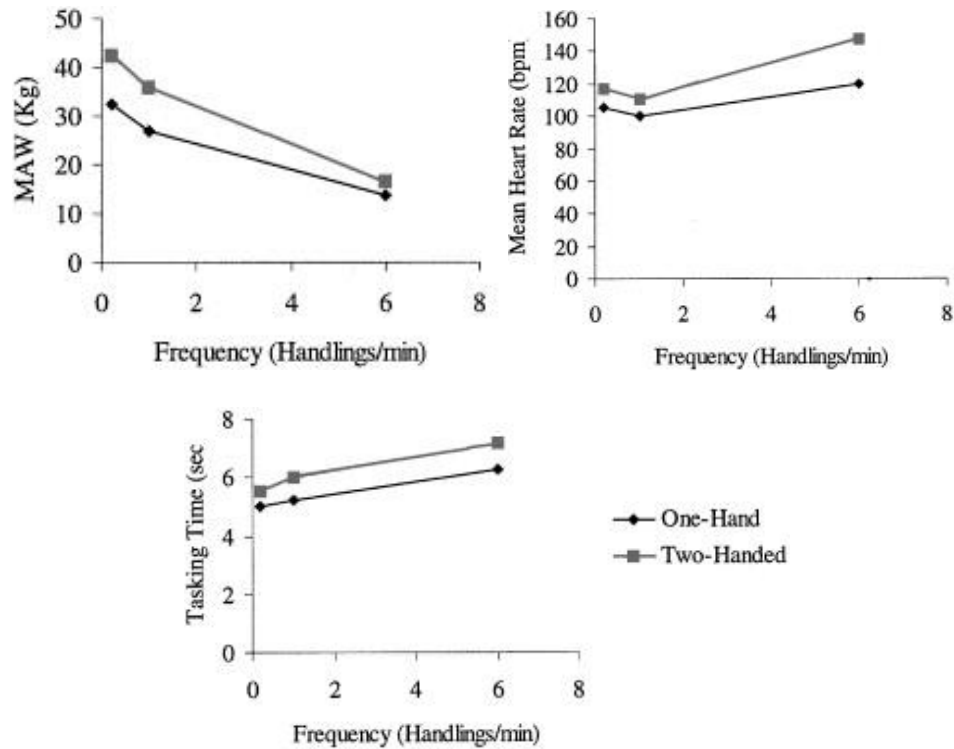


**Figure 3:** Figures from Yoon & Smith (1999) showing reduction in maximum acceptable weights (MAW), mean heart rate, and tasking time for one-handed MMH.

#### 2.4.2 Box width

Different movement patterns were observed when people were lifting boxes with different widths. Kingma et al. (2006) found that participants had greater lumbar flexion and trunk inclination when lifting a wide box (600mm) compared to a narrow box (300mm) (Kingma et al., 2006). Additionally, it was also found that squat lifting can be used to reduce spine compression force when the load is narrow enough to fit in between the feet (Kingma et al., 2006). However, stoop lifting might still be preferred given its lower metabolic cost compared to squat lifting (Garg & Herrin, 1979). Similarly, one-handed lifting might be preferred over two-handed lifting based on lower metabolic cost or lower mean heart rate (Figure 3), but the anthropometrical characteristics and the relative size

of the box to the participant should also be considered. On the other hand, Abadi et al. (2015) found an increase in mean heart rate and a reduction in mean self-perceived maximum acceptable weight of lift (MAWL) when lifting the large box compared to the small box (small: width: 33.4 cm, length: 56.2 cm, depth: 16.0 cm; large: width: 76.1 cm, length: 56.5 cm, depth: 22.0 cm). The decrease in MAWL when lifting larger boxes may push people to perform two-handed lifting so they can still lift the box of the same mass.

Grip span is also an important factor to consider along with box width for one-handed box lifts and transfers. Kong & Lowe (2005) found that participants rated cylindrical handles that ranged from 30-40mm in diameter the most comfortable to exert maximum grip forces, and total finger force capability would decrease with higher handle diameter. In another study looking at optimal handle separation for hand tools, Fransson & Winkel (1991) found that there would be a 10% reduction in resultant force between the jaws of hand tool with each 1cm increase in handle separation from the optimal grip span (50-60 mm for females and 55-65 mm for males). However, the above-mentioned optimal grip spans were tested with rigid handles, whether this range would extend to standard rectangular boxes with no handles have not been investigated. Though there have not been any studies looking at maximum grip span for rectangular boxes, Feix et al. (2014) found that people defaulted to grasp the smallest axis of an object, in which 96% of grasp locations were 7cm or less in width in a wide range of unstructured tasks, and it was believed that objects wider than 15cm could not be physically grasped with only one hand (Feix et al., 2014).

### 2.4.3 Box origin

Box origin could be another potential work factor affecting one versus two-handed lift decisions. Tang et al. (2020) found that people tended to deal with objects that were horizontally placed closer to them, lower to the ground, and required longer vertical travel distance (smaller H and greater D) with both of their hands compared to only one hand (Table 1). Even though Abadi et al. (2015) found no statistically significant differences in MAWL when lifting boxes to different heights, Weston et al. (2020) observed that some female subjects were unable to perform one-handed lifting at waist height due to having limited biceps strength. Furthermore, females could not rely on their body's momentum to lift the box mass off the shelf at waist height, while relying on body momentum for one-handed lifting could be an option for them at lower lifting heights. Therefore, two-handed lifting might be preferred over one-handed lifting at waist height for people with limited strength. It has generally been agreed that there would be an increase in both spinal compression and anterior-posterior shear with lower lift heights, but whether this increase in biomechanical exposure associated with lower lifting height would affect one versus two-handed lifting is yet to be investigated (Hoozemans et al., 2008; Weston et al., 2020).

Asymmetric lifting origin will lead to postural deviations and therefore affect lifting capacity. Previous studies suggested that one-handed lifts were associated with increased trunk flexion and lateral motion, especially when lifting from an asymmetric origin, compared to two-handed lifts (Allread et al., 1996). This difference in trunk kinematics may alter forearm, hand, and wrist posture and grip orientation to effectively grasp the box before and during the one-handed lifts, and therefore affect one-handed lifting capacity at varying box origins. Mogk & Keir (2003) suggested that wrist flexion at

45° could reduce maximum grip force by 40-50%, and forearm rotation from supination to pronation would also reduce grip force when the wrist was flexed. Additionally, it was found that grip strength was highest when the elbow was flexed at 90°, and was lowest when the elbow was flexed at 120° (compared to 0°, 30°, 60°), indicated height would also affect one-handed lifting capacity (Ng & Fan, 2001).

#### **2.4.4 Lift frequency**

Lift frequency or pace has been incorporated in the NIOSH lifting equation, and some studies have presented possible relationships between lift frequency and one-versus two-handed MMH decisions. Marras & Davis (1998) found that there were greater resultant trunk moment, maximum sagittal trunk flexion, and hip flexion when lifting with both hands. The psychophysical study conducted by Yoon & Smith (1999) further supported the above-mentioned biomechanical results. Despite lower perceived maximum acceptable masses or task capacity, one-handed-MMH resulted in lower mean heart rate and lower tasking time compared to two-handed MMH (Yoon & Smith, 1999). In a workplace setting, people may use the two-handed lift strategy when dealing with heavier objects given that they perceive that they can lift heavier loads with two hands, and use metabolic-cost efficient one-handed lift strategies to meet production quota or improve handling efficiency. As a result, an increase in lift frequency may lead to more often one-handed lifts.

#### **2.4.5 Expertise**

Expertise in MMH could play a role in determining movement strategies. It was found that the experienced manual material handlers bent their lumbar spine less by an average of 12° but bent their knees more by an average of 19° to position themselves

closer to the box when transferring boxes from the conveyer to a hand trolley, compared to novice manual material handlers (Plamondon et al., 2010). Given that people tend to handle boxes horizontally closer to them with both hands (Tang et al., 2020), and expert manual material handlers tend to get closer to the boxes, they might prefer the two-handed lift strategy over the one-handed lift strategy. Ergonomics training could be a reason for these differences as experienced manual material handlers were likely following the “back straight, knees bent, squat over stoop” safe lifting technique, while novices went with the more straightforward, efficient, and continuous stoop lifting when handling products (Plamondon et al., 2010). In addition to lifting, expertise was also found to have a significant impact on posture variables during a load transfer task, in which experienced manual material handlers showed less lumbar spine flexion, less trunk inclination, and more knee flexion than novices regardless of the direction of transfer (Plamondon et al., 2012). Therefore, the degree of MMH experience could influence whether an individual picks up a box with one or both hands.

#### **2.4.6 Sex**

Sex differences could have effects on one versus two-handed lift strategies. As identified by Plamondon et al. (2017), in comparison to males, females demonstrated sequential lifting patterns that could change from squat lifting to stoop lifting and put more stress on the lumbar spine during a palletizing task. Additionally, females were closer to their maximum lumbar flexion during the peak L5-S1 resultant moments, in comparison to males (Plamondon et al., 2017). Marras et al. (2003) also found that females made use of their hips more by about 6 degrees of pelvic flexion, whereas males made use of their lumbar spine flexion more by about 6 degrees when lifting. Whether these differences in

movement patterns will affect one- or two-handed lift decisions is unknown, but given males tend to have greater muscular strength compared to females of the same size, and people perceive that they can lift heavier loads with both hands (Yoon & Smith, 1999), females may prefer two-handed lifting over one-handed lifting for the same loads as well.

#### **2.4.7 Summary**

In general, potential task-related (box mass, box width, box origin, lift frequency) and personal determinants (expertise, sex) of one and two-handed lifting strategies have been identified or inferred from previous studies. It was found that people tend to deal with heavier objects that were horizontally placed closer to them and lower to the ground by using both of their hands compared to only one hand (Tang et al., 2020). Psychophysical factors including differences in perceived maximum available mass could contribute to the decision to lift heavier boxes with two hands (Yoon & Smith, 1999). Box width was found to influence people's movement patterns but its influence on one versus two-handed lifting was unknown, while several psychophysical factors such as perceived maximum acceptable mass, metabolic cost, and anthropometry could play a role (Abadi et al., 2015; Garg & Herrin, 1979; Kingma et al., 2006). Functional grip span would be a limiting factor for one-handed box lifting decision, but there has not been any maximum grip span testing on standard rectangular boxes. Lower box origin may push people to perform two-handed lifting instead of one-handed lifting, while individual strength could also play a role in this decision-making process (Tang et al., 2020; Weston et al., 2020). Postural deviations from varying lifting origin may also affect lifting capacity by changing the amount of grip force that can be exerted (Mogk & Keir, 2003). Other personal factors like expertise in MMH and sex could also affect the decision to use one or both hands

when handling objects, given that they influenced on individual's movement patterns (Marras et al., 2003; Plamondon et al., 2010, 2012).

#### **2.4.7 Thesis direction**

To align with the timeline of a Master's-level thesis, the research focused on three of the four task-related factors: box mass, box width, and box origin (i.e., shelf height). The research determined the maximum box width and box mass that one could comfortably and safely transfer with one hand from varying shelf heights. The influence of grip orientation and shelf height on maximum box width and box mass were also investigated.

## Chapter 3: Research Questions and Hypotheses

### 3.1 Research question

Among healthy, able-bodied individuals performing a series of box transfer tasks:

**Study 1:** What is the perceived maximum acceptable box dimension for each combination of grip orientation (top, front) and shelf height (ankle, GT, shoulder)? Do grip orientation and shelf height affect the perceived maximum box dimension that one can be transferred with only one hand comfortably and safely?

**Study 2:** What is the perceived acceptable maximum box mass for each combination of grip orientation (top, front) and shelf height (ankle, shoulder) when the box is set at perceived maximum grip span determined from Study 1? Do grip orientation and shelf height affect the perceived maximum box mass that one can be transferred with only one hand comfortably and safely?

### 3.2 Hypothesis

Consistent with Plamondon et al. (2012), it was hypothesized that both task-related characteristics (grip orientation and shelf height) would influence the perceived maximum acceptable box dimensions and box masses that one can be transferred with only one hand. Since elbow would be more likely close to 90° and wrist would be less deviated from neutral posture when grabbing the box from the front at ankle and GT heights, and therefore could exert more grip force, it was hypothesized that shoulder height would have lower perceived maximum acceptable lifting capacity compared to the other two heights. Since the wrist would be more likely in a neutral or close-to-neutral posture when grabbing

the box from the front, it was hypothesized that perceived lifting capacity would be lower if the box needs to be grabbed from the top.

## **Chapter 4: Methods**

### **4.1 Participants**

Two sex-balanced samples of 20 participants each (10F, 10M) healthy, able-bodied participants were recruited from a population of university students to complete a series of box transfers from a shelf to a table that was set at greater trochanter (GT) height for the two studies. The shelf was set 1 meter away from the table. The sample size was determined using G-Power (version 3.1.9.7), in which the alpha value was 0.05, the power was 80%, and the partial-eta-squared was 0.14 (Faul et al., 2009) (Appendix E). Participants completed the Standardized Nordic Questionnaire (Appendix B) to screen for presence and location of pain or discomfort in various body regions. Participants who self-reported experiencing pain or discomfort in the last 7 days were excluded to minimize the risk of worsening the existing symptoms from experimental protocols (Appendix B). Additionally, participants completed a demographics form to gather information about their sex, age, height, body mass, program of study, experience with MMH, and if they have received any MMH lifting training (Appendix C). Participant's handedness was determined by Edinburgh Handedness Inventory (Appendix D).

### **4.2 Experimental design**

A repeated measure design was used to address the research questions. This thesis study consisted of two, 2-hour studies. While a sex-based statistical comparison was not motivated by the research questions, a sex-based comparison was included (Appendix I) to inform future hypotheses.

### 4.2.1 Study One

For Study 1, maximum acceptable grip dimension was recorded in two grip orientations (top, front) and at three shelf heights (ankle, GT, shoulder) (6 conditions). Each condition was repeated 10 times at a randomized order, there were  $6 \times 10 = 60$  box transfers for each session.

The top shelf was set at participant's shoulder height, the middle shelf set at participant's greater trochanter (GT) height, and the bottom shelf was set at fixed height at 10cm, mimicking ankle height. The table where boxes were transferred to was set at GT height (Figure 4).

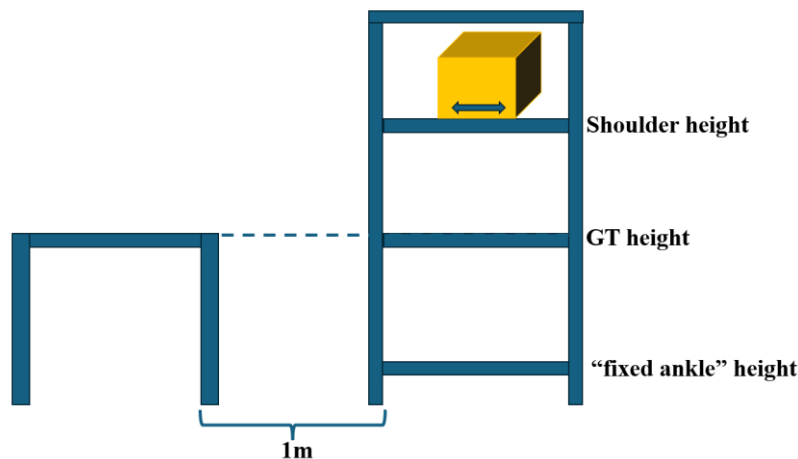


**Figure 4:** Experimental setup for Study 1.

### 4.2.2 Study Two

For Study 2, there were two grip orientations (top, front) and two shelf heights (ankle, shoulder). The GT conditions were removed for Study 2 to reduce mental and physical fatigue (4 conditions). And since each condition was repeated 10 times at a randomized order, there were  $4 \times 10 = 40$  box transfers for each session. The box for

Study 2 was 8 cm taller than Study 1 to create sufficient volume to add more mass. Therefore, the shoulder height shelf and the table were lowered by 8cm from shoulder and GT, respectively, such that the hand grasp vertical height was the same as Study 1 (Figure 5).

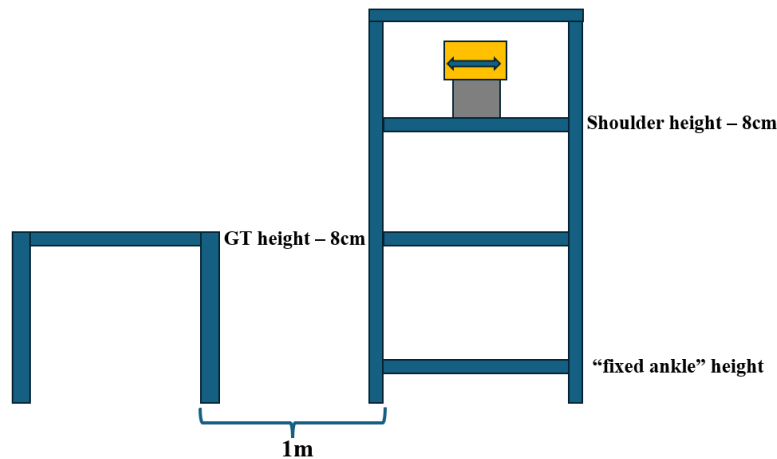


**Figure 5:** Experimental setup for Study 2.

### 4.3 Experimental protocol

Participants repeated the box transfer activities for all combinations of grip orientation and shelf height with their dominant hands with 5-points of contact, meaning that the thumb and all 4 finger pads needed to be in contact with the cardboard surfaces of the box throughout the transfer. Set verbal instructions (Appendix F) were given to participants on where to grab the box (top or front) and what to adjust depending on the study (box dimension or box mass).

#### 4.3.1 Study One

A minimally weighted retractable box (0.494kg, width: to be adjusted, depth: 10cm, height: 10cm) was used for Study One (Figure 6). A set of 10 randomized starting

dimensions ranging from 47mm to 157mm were generated using a MATLAB script, and they were assigned such that each randomized starting dimension was paired exactly once with each of the 6 conditions, ensuring a balanced design. The trial order was randomized, but assignment of starting dimensions to conditions were balanced. In other words, the 10 numbers generated for starting dimensions were fully randomized and different, but each number was only assigned to each condition once. For example, a randomized starting dimension of 120mm would only be assigned to each of the 6 conditions once. Participants were asked to grab the box either from the front or top and expand/collapse the corresponding box dimension until they perceived that they could no longer transfer the box with only one hand comfortably and safely. Participants had unlimited number of width adjustments until they perceived that they'd reached their maximum dimension for comfortability and safety. The maximum width of the adjusted dimension was measured and recorded. Participant's hand length (distance between stylium landmark of the wrist and middle fingertip) was measured to normalize the results. The averaged normalized box width (in %hand length) of last 3 trials for each condition was used as the maximum grip span for Study Two. The averaged absolute box width (in mm) of last 3 trials for each condition was used in statistical analysis.

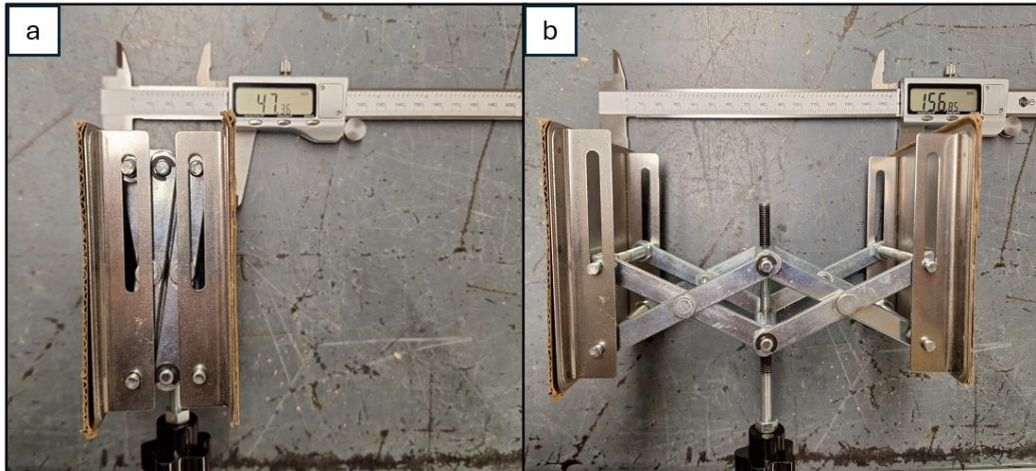


**Figure 6:** Retractable box in fully closed (a) and fully open (b) positions.

#### 4.3.2 Study Two

The retractable box was set at different maximum grip spans determined from Study One, depending on the condition (top-shoulder: 70% hand length; top-ankle: 73% hand length; front-shoulder & front-ankle: 71% hand length). The box was attached to an empty box (305g) and filled with loose lead shots to a randomized starting mass (Figure 7). Similar to previous psychophysical study conducted by Snook & Ciriello (1991), loose lead shots were used since they could provide a continuous dependent measurement of box mass.

A set of 10 randomized starting masses of just the lead shots plus the empty box ranging from 500g to 3000g were generated using a MATLAB script, and they were assigned such that each randomized starting mass was paired exactly once with each of the 4 conditions, ensuring a balanced design. In other words, the 10 numbers generated for starting masses were fully randomized and different, but each number was only assigned to each condition once. For example, a randomized starting mass of 700g would

only be assigned to each of the 4 conditions once. The lower limit of 500g was used to ensure the box always had some lead shots to start with, and upper limit was used since it was a value way above what pilot participants had been able to lift comfortably and safely, but still under recommended one-handed mass limit of 5.1kg (for holding a limb in orthopedics setting) and observed upper bound of mass that people tended to handle with only one hand (9.41kg) (Tang et al., 2020; Waters et al., 2009). The trial order was randomized, but the assignment of starting masses to conditions were balanced. Once the metal box was filled with a randomized amount of lead shots, it was attached to the retractable box via a fixing device (726g), so the whole device mass ranged from 1226g to 3726g. Up to 11.34kg lead shots were stored in a bigger box to the left of the participants for mass adjustments, so that lead shots in the metal box could be easily added or removed as participants desired (Figure 7).

Participants were asked to either grab the box from the top or from the front and attempt to transfer the box that had an unknown starting mass. If they perceived that it was not the maximum box mass they could transfer, the metal box would be detached, and participants were asked to add/remove lead shots into to the metal box themselves until they perceived that they could no longer transfer the box with only one hand comfortably and safely. Participants had unlimited number of mass adjustments until they perceived that they'd reached their maximum mass for comfortability and safety. Unlike Snook & Ciriello (1991), participants did not always work on an incentive basis since the randomized starting mass could be very heavy, especially given that it was set at maximum grip spans determined from Study One. Participants could reduce the mass inside the box as they desired, but they were not allowed to remove all the lead shots

from the box, and those who could not lift more than the empty box (1031g) were excluded from the study. This exclusion criterion was set to avoid lack of variability in dependent variable (final adjusted box mass). While this might limit generalizability to people with lower one-handed lifting capacity, it was necessary so that meaningful changes in the dependent variable across different conditions could be captured. The final adjusted mass of the box was measured. The averaged absolute box mass (in g) of last 3 trials for each condition was used in statistical analysis.

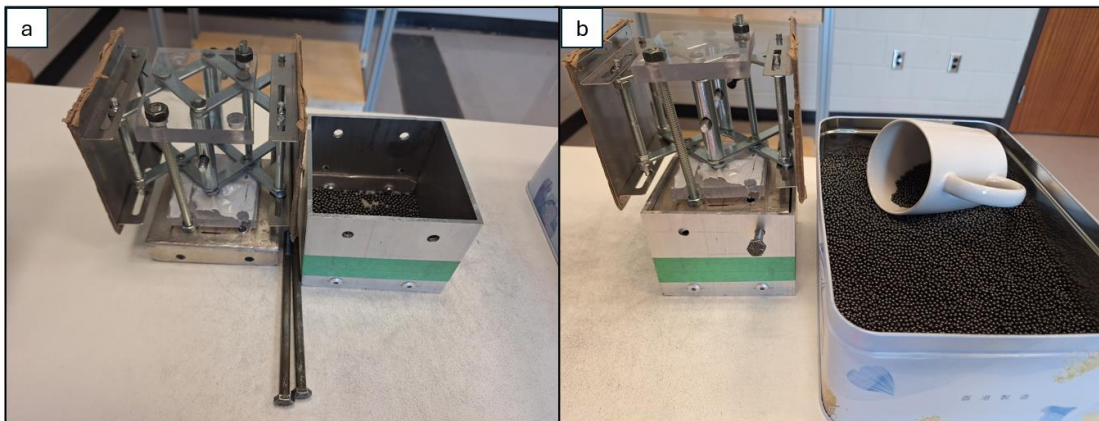


**Figure 7:** (a) Disassembled retractable box and metal box used to hold lead shots, and (b) assembled retractable and metal box with bin of additional lead shots that can be added/removed from the metal box.

#### 4.4 Statistics

A within-subject repeated measure ANOVA (2 grip orientations x 3 shelf heights OR 2 grip orientations x 2 shelf heights) with an alpha value of 0.05 were used. All the ANOVA assumptions were met. In both studies, the last 3 measurements of each condition were found to capture participant's stable performance since variability from initial exploratory phase had subsided. Those 3 last measurements of each condition in

absolute terms (perceived maximum box dimension in millimeters and perceived maximum box mass in grams) were averaged and put into the ANOVA model. Given that significant grip orientation x shelf height interaction effect was observed for Study One, post hoc Tukey's test was performed for pairwise comparisons. All statistical analysis were conducted using RStudio (version 2025.051+513), lme4 package, lmerTest package, effectsize package, and car package (Bates et al., 2015; Ben-Shachar et al., 2020; Fox & Weisberg, 2019; Kuznetsova et al., 2017; R Core Team, 2025).

## Chapter 5: Results

### 5.1 Demographics

Participant demographics are detailed in Tables 2 and 3. Aligned with the general population, most of the participants were right-handed. All participants completed box transfer tasks with their dominant hand. All participants for Study One met the inclusion criteria. One participant for Study Two was excluded from the study since the participant could not lift more than the empty box. The excluded participant's demographics are not included in Table 3. Distributions of perceived maximum box width and perceived maximum box mass as a function of hand lengths are outlined in Appendix I.

**Table 2:** Participant demographics for Study One.

|                       | <b>n</b>    | <b>20</b> |
|-----------------------|-------------|-----------|
| <b>Sex</b>            | F           | n = 10    |
|                       | M           | n = 10    |
| <b>Handedness</b>     | L           | n = 4     |
|                       | R           | n = 16    |
|                       | <b>Mean</b> | <b>SD</b> |
| <b>Age (years)</b>    | 24.55       | 4.91      |
| <b>Height (cm)</b>    | 171.43      | 8.49      |
| <b>Body mass (kg)</b> | 71.01       | 12.33     |

**Table 3:** Participant demographics for Study Two.

|                      | <b>n</b>    | <b>20</b> |
|----------------------|-------------|-----------|
| <b>Sex</b>           | F           | n = 10    |
|                      | M           | n = 10    |
| <b>Handedness</b>    | L           | n = 2     |
|                      | R           | n = 18    |
|                      | <b>Mean</b> | <b>SD</b> |
| <b>Age (years)</b>   | 24.55       | 4.29      |
| <b>Height (cm)</b>   | 171.60      | 7.94      |
| <b>Body mass(kg)</b> | 66.77       | 15.37     |

## 5.2 Study One

A significant grip orientation x height interaction was found (Table 4). Post-hoc analysis revealed that the mean perceived maximum acceptable box width when grabbed from the top was significantly higher compared to grabbing the box from the front at both ankle and GT shelf heights (Figure 8). When grabbing the box from the top, the mean perceived max box widths from shoulder height shelf were statistically significantly lower than from GT and ankle shelf heights (Figure 9).

**Table 4:** Summary of statistical main and interaction effects for the mean perceived max box width when grabbed from the front or top of the box across three shelf heights.

| Measurement | Main/Interaction Effects | F-Statistic | P-Value | Partial Eta Squared |
|-------------|--------------------------|-------------|---------|---------------------|
| Box Width   | Grip Orientation         | 18.61       | < 0.05  | 0.16                |
|             | Height                   | 10.58       | < 0.05  | 0.18                |
|             | Interaction              | 10.62       | < 0.05  | 0.18                |



**Figure 8:** Grip orientation's effects on mean ( $\pm$ SE) perceived max box width, in millimetres (mm) when grabbed the box across three shelf heights.



**Figure 9:** Shelf height's effects on mean ( $\pm$ SE) perceived max box width, in millimeters (mm) when grabbed from the front or top of the box.

Perceived maximum box width (70-73% hand length) was consistent when grabbing the box from the front regardless of shelf height but decreased with higher shelf height when grabbing the box from the top (Table 5).

**Table 5:** Maximum grip span (% hand length) averaged for each condition across 20 participants.

| Shelf Height    | Grip Orientations |      |       |      |
|-----------------|-------------------|------|-------|------|
|                 | Top               |      | Front |      |
|                 | Mean              | SE   | Mean  | SE   |
| <b>Ankle</b>    | 73%               | 1.5% | 71%   | 1.4% |
| <b>GT</b>       | 73%               | 1.4% | 71%   | 1.3% |
| <b>Shoulder</b> | 70%               | 1.5% | 71%   | 1.5% |

## 5.2 Study Two

No significant interaction effects were observed; however, significant main effects for grip orientation and shelf height were observed (Table 6). The mean perceived maximum acceptable box mass when grabbed from the front was significantly higher than when grabbed from the top at both ankle and shoulder heights (Figure 10). The mean perceived maximum acceptable box mass when grabbed from ankle height were significantly higher regardless of grip orientation (Figure 11).

**Table 6:** Summary of statistical main and interaction effects for the mean perceived max box mass when grabbed from the front or top of the box across two shelf heights.

| Measurement | Main/Interaction Effects | F-Statistic | P-Value | Partial Eta Squared |
|-------------|--------------------------|-------------|---------|---------------------|
| Box Mass    | Grip Orientation         | 18.98       | < 0.05  | 0.25                |
|             | Height                   | 17.32       | < 0.05  | 0.23                |
|             | Interaction              | 0.25        | > 0.05  | 4.42e-03            |

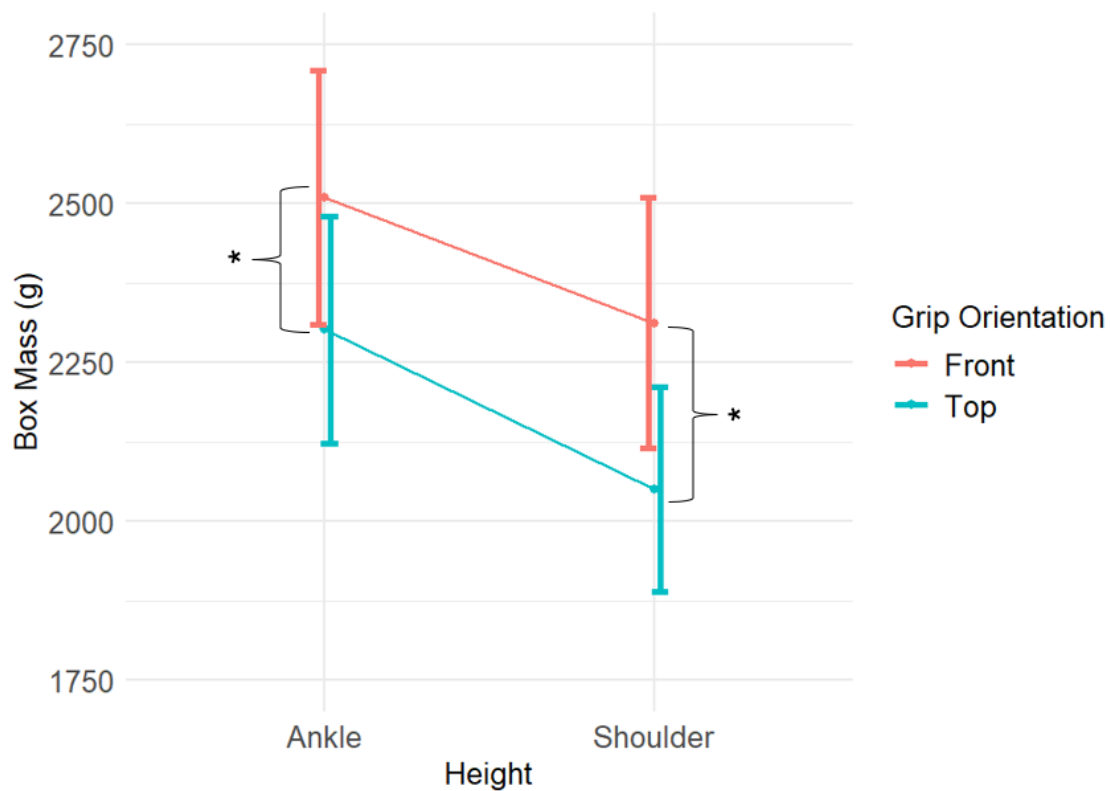


**Figure 10:** Grip orientation's effects on mean ( $\pm$ SE) perceived max box mass, in grams (g) when grabbed the box across two shelf heights.

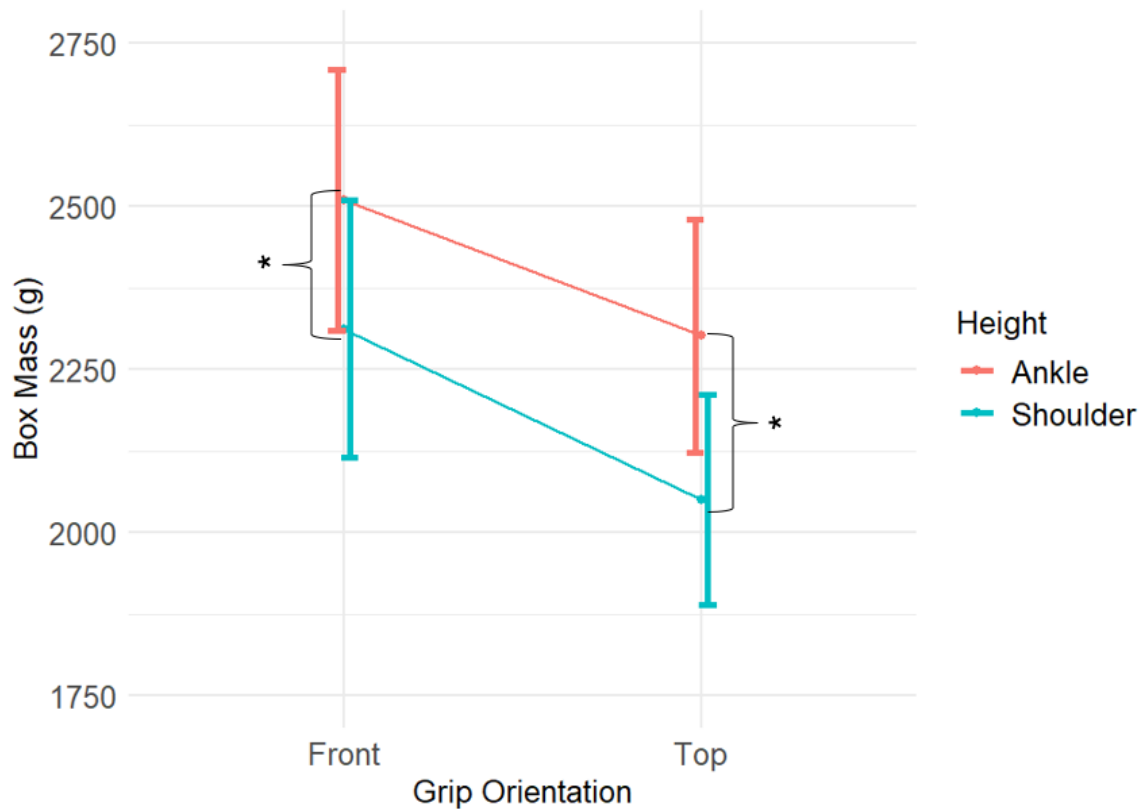


**Figure 11:** Shelf height's effects on mean ( $\pm$ SE) perceived max box mass, in grams (g) when grabbed from the front or top of the box.

To contextualize findings on the maximum perceived box mass, data were expressed relative to sex and age specific-grip strength normative data (Appendix J). To express data relative to grip strength, calculations described in Appendix G were used to estimate the grip force necessary to provide sufficient friction to support the maximum perceived box masses. It was found that participants on average exerted 13.9% to 16.9% grip strength to transfer boxes across different conditions (Figure 12, Table 7), relative to the maximum grip strength measured at handle position 5 of a Jamar hand dynamometer by Trampisch et al. (2012).

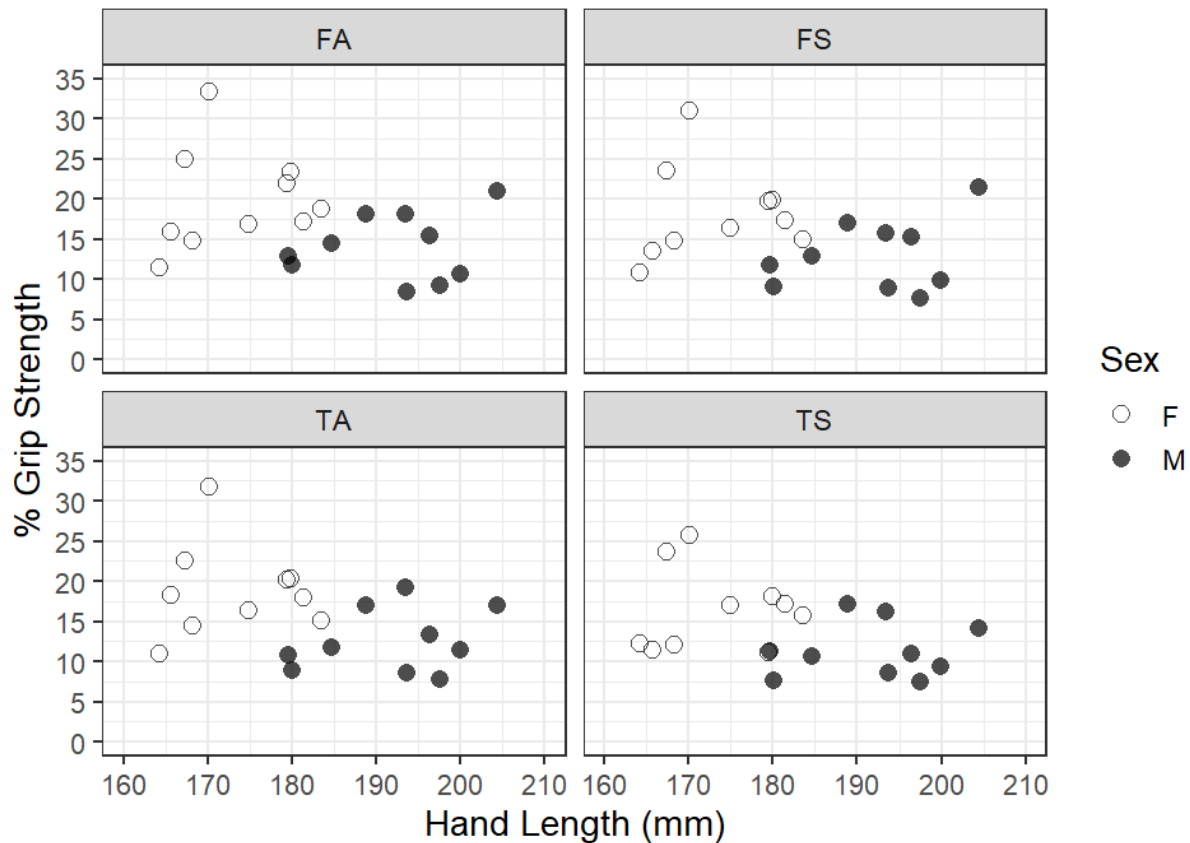


**Figure 12:** Perceived maximum acceptable box mass, across 2 grip orientations (T-Top; F-Front) and 2 shelf heights (A-Ankle; S-Shoulder), relative to normative grip strength reported in Trampisch et al. (2012).

While grip force could be a limiting factor in determining the maximum perceived mass for a one-handed lift, wrist joint strength could also be a limiting factor. To contextualize the findings, maximum perceived box mass and the equations described in Appendix H were used to estimate the corresponding wrist moment, where the wrist moment was expressed relative to sex-specific wrist joint strength of young, healthy university aged participants (Appendix J). It was found that participants on average exerted 36.7% to 41.7% wrist joint strength to transfer boxes across different conditions, relative to the maximum

wrist radial deviation and extension strength reported by La Delfa et al. (2015) (Figure 13).

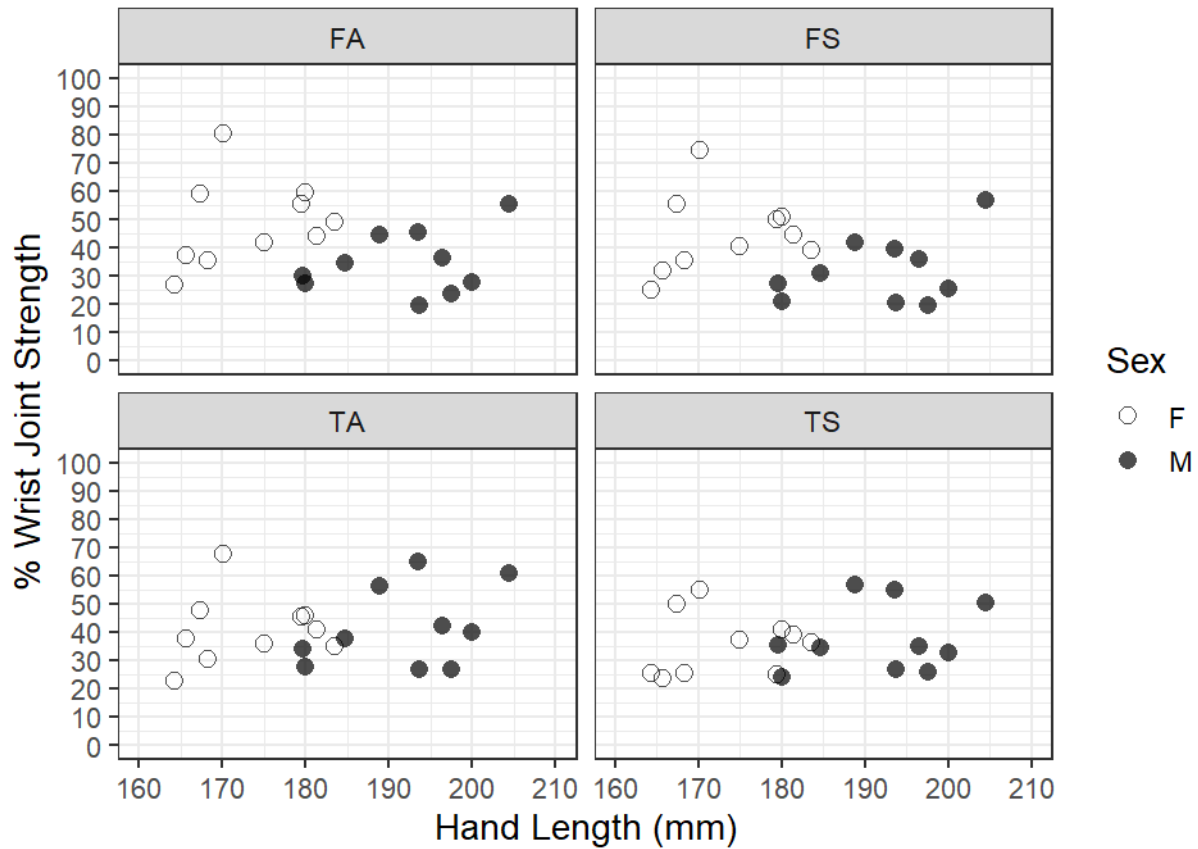


**Figure 13:** Wrist torque required to transfer boxes across 2 grip orientations (T-Top; F-Front) and 2 shelf heights (A-Ankle; S-Shoulder), relative to normative wrist extension (for Top grasps) and radial deviation (for Front grasps) strength reported in La Delfa et al. (2015).

**Table 7:** Mean grip force and wrist torque ( $\pm$ SD) across conditions, expressed relative to reported population norms.

|           | %Grip Strength |      | %Wrist Strength |       |
|-----------|----------------|------|-----------------|-------|
|           | Mean           | SD   | Mean            | SD    |
| <b>FA</b> | 16.9%          | 6.0% | 41.7%           | 15.1% |
| <b>FS</b> | 15.6%          | 5.7% | 38.4%           | 14.2% |
| <b>TA</b> | 15.7%          | 5.7% | 41.3%           | 12.9% |
| <b>TS</b> | 13.9%          | 5.0% | 36.7%           | 11.3% |

*Note: FA = Front-Ankle; FS = Front-Shoulder; TA = Top-Ankle; TS = Top-Shoulder*

## **Chapter 6: Discussion**

The overall purpose of this investigation was to gain a better understanding of the task factors (box width, box mass, box origin) that drive the decisions to use one or two hands when completing box lifting and transfer tasks. The influence of potential modifying factors, such as grip orientation and shelf height, on the perceived maximum box width and box mass for one-handed lifts and transfers were investigated. The hypotheses that shoulder height and top grasp would reduce perceived maximum one-handed lifting capacity were supported.

### **6.1 Perceived maximum box width for one-handed transfers**

The absolute perceived maximum acceptable box width found in study one was larger than what have been found in previous observational studies, although they did not exceed known limits. By analyzing human grasping behaviour in a wide range of unstructured tasks, Feix et al. (2014) found that people defaulted to grasp the smallest axis of an object, in which 96% of grasp locations were 7cm or less in width. However, all the participants perceived that they could transfer boxes greater than 7cm wide regardless of condition in Study One. This discrepancy could be due to different objects used. The box used in the study was in rectangular shape and had cardboard attached to the sides to mimic a standard cardboard box in a warehouse. Meanwhile, observations by Feix et al. (2014) were based on objects in varying shapes and grip surfaces. Irregular or curved shapes may limit how wide thumb and fingers could spread. Smooth and slippery surfaces would reduce friction and making it hard to stabilize the object, therefore people may narrow their grips to maintain stability and control. Results from Study One also indicated that maximum grip span ranged from 13.3cm to 13.8cm (70-73% hand

length) depending on conditions (Figures 7 and 8, Table 5). This finding aligned with the previous research that objects wider than 15cm could not be physically grasped with one hand (Feix et al., 2014).

Though the absolute difference between orientations and heights were small (<5mm), perceived maximum box widths were still statistically significant different when grabbing the box from the top off shoulder height shelf compared to the two lower heights. The reduced perceived maximum box width at Top-Shoulder condition could be due to a combination of postural constraints, reduced grip strength, and lack of visual guidance.

Participants adjusted their hand/wrist and forearm posture to match object orientation and lifting height, and therefore affected the maximum grasp aperture and perceived maximum box width. For the Top-Shoulder condition specifically, more wrist flexion was needed when grasping the box from top at shoulder height shelf since the arm was lifted higher. With the wrist joint approaching range of motion limits in this awkward posture, maximum grasp aperture was lowered since this wrist flexion would limit finger extension to grab a wider object (Monsabert et al., 2023). This awkward posture also led to reduced grip strength. Wider elbow angle was needed so the arm could be lifted higher to orient hand to the shoulder height shelf. Previous work has demonstrated that lower grip forces occurred when the elbow was flexed at 120° compared to 0°, 30°, 60°, 90° positions (Ng & Fan, 2001). More wrist flexion was needed to grasp the box from the top at shoulder height, and it was found that wrist flexion at 45° could reduce grip strength by 40%-50% (Mogk & Keir, 2003). Additionally, muscle's ability to generate force is dependent on its length and the optimal muscle length to maximize force production would be around its resting length (Winter, 2009). Grip force production

decreased when wrist and forearm flexors were over-shortened at the awkward posture. Therefore, people may adopt a narrower grip span to maximize their ability to apply force to stabilize the boxes so that they could transfer the box comfortably and safely.

Additionally, limited line of sight of the top of the box could also have negatively affected the perceived maximum box width the participants were willing to lift and transfer. Previous study found that people reported lower perceived grasp aperture when lifting heavier cylindrical canisters compared to the lighter ones without actually seeing them, despite that all the cylindrical canisters were the same width (Butler et al., 2015). Even though the above-mentioned study was looking at the mass' influence on perceived grasp aperture, it implied that more effort could reduce perceived grasp aperture. Similarly, it was possible that higher elevation and lack of visual guidance at Top-Shoulder condition increased the effort needed to transfer the box, and therefore made participants underestimate maximum liftable box width to maintain control, especially when the wrist was at a non-neutral posture with reduced grip strength. Additionally, Héroux et al (2024) observed that high-level perceptual judgments of object width tended to be less accurate and underestimated when visual context was limited or occluded. This finding led to the speculation that lack of visual guidance at Top-Shoulder condition may have reduced perceived maximum liftable box width.

## **6.2 Perceived maximum box mass at perceived maximum box width**

The perceived maximum acceptable box mass at maximum grip span determined from Study Two was lower than the one-handed lifting limits that previous studies proposed and was affected by both grip orientation and shelf height. There has not been any well-adopted and published recommended mass limit for one-handed lifting. The

more commonly used recommended mass limit for two-handed lifting is 23kg under ideal conditions (Snook & Ciriello, 1991). While some may argue that recommended mass limit for one-handed lifting is roughly half of 23kg (11.5kg), it has not been directly tested and could vary depend on ergonomics context. This value will likely be lowered with increasing number of repetitions, asymmetry, and poor coupling. Lifting frequently with insufficient recovery would lead to muscle fatigue and increased risk of injury, increase in asymmetry would increase spinal compression and shear forces, and poor coupling would require higher maximum grasp force and therefore would all reduce acceptable mass for lifting (McGill et al., 2013; Waters et al., 2021; Weston et al., 2020). Kilbom et al. (1992) suggested that prolonged one-handed carrying should not exceed 6kg or 10kg for women or men respectively to avoid cardiovascular and muscle fatigue. Waters et al. (2009) suggested that the recommended mass limit for one-handed lifting and holding limbs is 5.1kg in orthopedics setting, and this value was calculated using 75<sup>th</sup> percentile shoulder flexion strength and endurance capability for US women. It was found that people adopted one-handed lifting when the object was  $12.07 \pm 8.68$ lbs ( $5.47 \pm 3.94$ kg) in the cross-sectional survey study conducted by Tang et al. (2020), without accounting for object shapes or types. However, object characteristics and dimensions were different or not considered in the above-mentioned studies. For example, Kilbom et al. (1992)'s recommended mass of carrying was derived from carrying a case with padded handle, which likely greatly increased acceptable mass since it had a good coupling factor. Waters et al. (2009)'s suggestion was made upon 75<sup>th</sup> percentile female strength, and Tang et al. (2020) did not specify what objects have been handled, how wide they were, and if they had handles. Study Two results generally aligned with the lower bound observations by

Tang et al. (2020), where the perceived maximum acceptable box mass ranged from 2.05kg to 2.51kg when the box dimension was set at the maximum grip span.

Previous psychophysical study conducted by Lee & Hwang (2020) found that the maximum acceptable and comfortable one-handed lifting height decreased with heavier load. These observations aligned with findings from Study Two in that the perceived maximum box mass at shoulder height was lower than that of ankle height, regardless of grip orientation (Figure 10). Biomechanical exposure data from other studies further supported that height had significant effect on one-handed lifting capacity. Lifting from higher heights would result in higher neck and shoulder muscle activities, higher spinal compression, and higher shear forces (Amar et al., 2017; Davis & Marras, 2005). To reduce above mentioned biomechanical exposure, one likely reduced the amount of mass lifted from higher shelves, therefore explaining why perceived maximum acceptable box masses were lower from shoulder height compared to ankle height in Study Two.

Lower maximum acceptable box masses when grasping the box from the top compared to front were likely due to a combination of muscle inefficiency, biomechanical disadvantage, and lower perception of stability. Muscle's ability to generate force is dependent on its length and the optimal muscle length to maximize force production would be around its resting length (Winter, 2009). Grip force production decreased when wrist and forearm flexors were over-shortened with top grasps since more wrist flexion was needed, therefore reduced maximum acceptable box mass. In contrast, grasping from the front maintained the wrist in a more extended and the forearm in a more neutral posture, which placed the flexors and extensors muscles in their more optimal muscle length and force relationship to produce higher grip force (Mogk and Keir 2003).

Additionally, top-grasps were less mechanical-efficient compared to front-grasps. As the hand was in a horizontal orientation when grasping the box from the top, higher wrist extensor forces were needed to counteract gravity, indicated that additional muscle demand was needed to keep the grip orientation to counteract the rotational torque, making top-grasped box transfers more challenging (Shah et al., 2017). Though all participants were instructed to maintain 5-points of contact throughout box transfers for both grip orientations, front grasps often have higher surface contacts than top grasps. Gravity pulled the weighted box down so it would slip slightly downward as it was lifted off the shelf. Any downward motion would reduce the contact area for top grasp, while finger pads would just be shifted up slightly toward the upper border but preserve the contact area for front grasps. Higher contact area would provide more cutaneous feedback for better grip control (Augurelle et al., 2003). Therefore, participants may perceive that they could lift heavier mass when grasping the box from the front.

Although males typically have higher absolute grip and wrist strength than females (Appendix J), the relative strength exerted to transfer perceived maximum weighted boxes was comparable between sexes across all conditions in Study Two, with females having slightly higher values on average (Figures 12 and 13). Males had generally higher perceived maximum box mass compared to females yet exerted slightly lower relative grip strength and wrist strength on average. These findings aligned with previous research that females occasionally had higher wrist extension strength relative to their body mass compared to males, though they generally had lower absolute wrist strength (Napper et al., 2023). On the other hand, the comparable relative wrist torques less than 41.7% across all conditions suggested that wrist strength might not be a limiting factor for

participants to lift a heavier box, and they might have determined their perceived maximum acceptable box mass based on other factors. The actual grip strength that participants exerted to transfer boxes across different conditions were likely greater than values shown in Figure 12 and Table 7. There have not been any studies tested grip strength on maximum hand span. Maximum grip strength reported by Trampisch et al. (2012) was determined using Jamar Dynamometer at handle position 5. Though handle position 5 was the widest setting for Jamar Dynamometer, its width (~8.57cm) was lower than the set box widths (13.3cm-13.8cm) in Study Two. Since each centimeter increase away from the optimal grip span (50-60 mm for females and 55-65 mm for males) could lead to 10% reduction in force production (Fransson & Winkel, 1991), the maximum grip strength at 13.3-13.8cm would be much lower than the values reported by Trampisch et al. (2012), therefore the actual % grip strength exerted would be much higher in Study Two.

### **6.3 Study significance and implications**

The study findings reinforced and supported existing ergonomics guidelines. It can be inferred from the current investigation that top-only grips or far reaches should be avoided to reduce awkward posture, and heavy or wide items should not be placed at shoulder height or above. This aligned with NIOSH's suggestion that workers should be able to wrap their hands around the object without causing excessive wrist deviations in manual material handling (Waters et al., 2021). OSHA suggested that heavy objects should be stored at waist level, platforms and conveyors should be built around waist level as well to minimize awkward posture. Lifting should be performed between knuckle and shoulder height, and that the recommended lifting limits calculated by NIOSH

equation will be reduced by 22.5% at shoulder height or above (*Ergonomics Program. | Occupational Safety and Health Administration, 1999.*).

Although the absolute differences in perceived maximum box width and perceived maximum box masses were small across different conditions, it was consistent that grasping boxes from the top while on a shoulder height shelf significantly reduced the maximum perceived one-handed lifting capacity. Even though the absolute changes (5mm in box width and 500g in box mass) were small, they still present meaningful biomechanical and perceptual cost for less favourable grip configurations (top grip) and higher reaches (shoulder height), and they could accumulate to fatigue or risk in a job that requires repetitive box lifting and transfers, especially in a warehouse or industrial setting. A proper workplace spatial layout with optimized box orientation and working heights should be considered to preserve worker confidence and capacity, enhance safety, and improve worker performance in manual material handlings.

The perceptual thresholds for box widths and box masses and task constraints like grip orientation and shelf height can be used by DHM users to generate more realistic simulations. Whether the avatar is going to reach the box with one or two hands can be better predicted based on task characteristics. If the 5th-percentile female hand length of 164mm (Gordon et al., 2012) was used as the reference for ergonomic design in warehouse operations, and if the box is narrower than 124mm (Figure 14) and lower than 36.7% wrist strength was needed, one-handed box transfer should also be simulated in DHM instead of only two-handed box transfers for a more comprehensive ergonomics risk assessment.

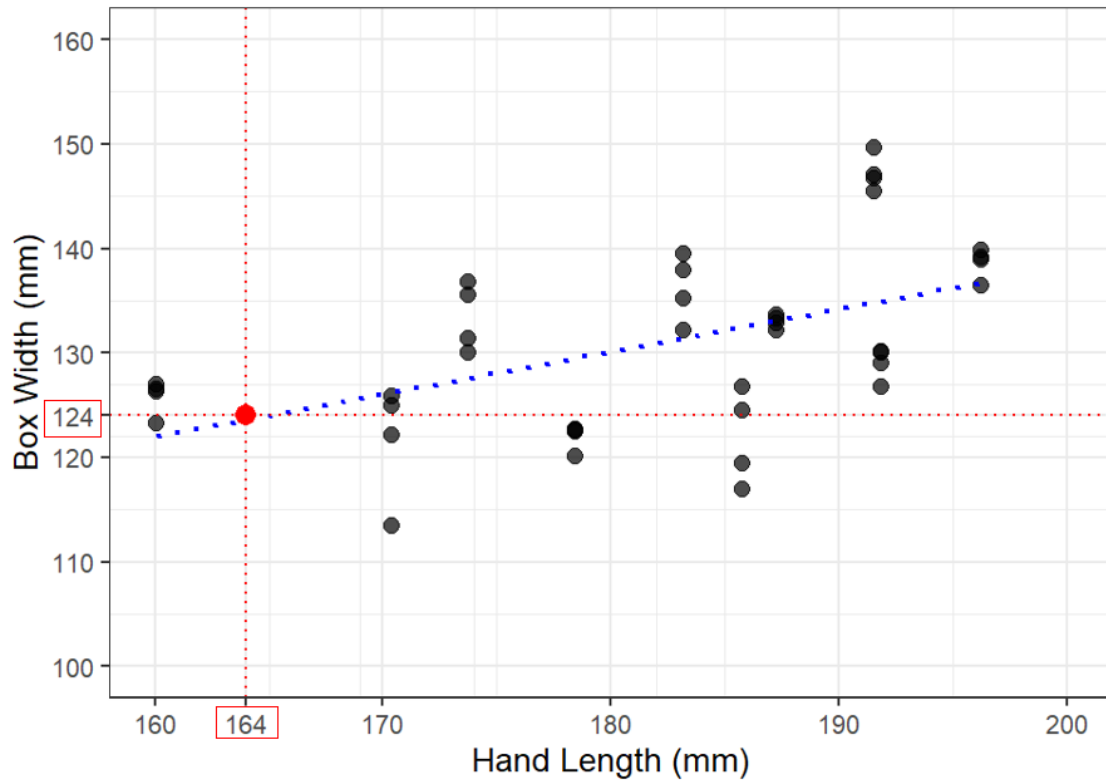


**Figure 14:** Perceived maximum box width across Front-Ankle, Front-GT, Front-Shoulder, and Top-Shoulder conditions of female participants, and predicted perceived maximum box width based on 5th percentile female hand length.

#### 6.4 Limitations and future directions

Since the studies were conducted in a controlled laboratory setting, it may not reflect the dynamic and complexities of real work conditions (i.e. required work pace, distractions, limited spacing in between boxes) of an actual manual material handling task. Since the studies were conducted on healthy, able-bodied young university students, findings may not be generalizable to experienced or older industrial workers or people with existing MSDs. The retractable device used in the study had cardboard attached to the sides to mimic a standard cardboard box in a warehouse, so findings can not be

extended to boxes with ergonomics handles, slippery surfaces, irregular shapes or unstable loads. Based on the results, people may lift with only one hand when the box requires less than 36.7% wrist strength, and the box width is less than 124mm. Future studies can assess whether the same maximum perceived grip widths and masses determined from the current investigation can hold across objects of different shapes and grip surfaces for one-handed liftings/transfers. This will provide insight into tool and part design in industrial settings.

## **Chapter 7: Conclusion**

This psychophysical study provided insights into perceived maximum box widths and masses people perceived that they could lift comfortably and safely. DHM users can use this information to more accurately decide when to model an avatar reaching a box with one or both hands. Both grip orientation and shelf height significantly influenced perceived lifting capacity as the perceived maximum box width was lowered when gripping the box from the top off of a shoulder height shelf, and perceived maximum box mass was reduced when gripping the box from the top or from a shoulder height shelf. Findings reinforced established ergonomics guidelines on box orientation and placement in workplace settings. Future studies can investigate whether the current findings and maximum limits will hold across objects of different shapes or grip surfaces or unstable loads.

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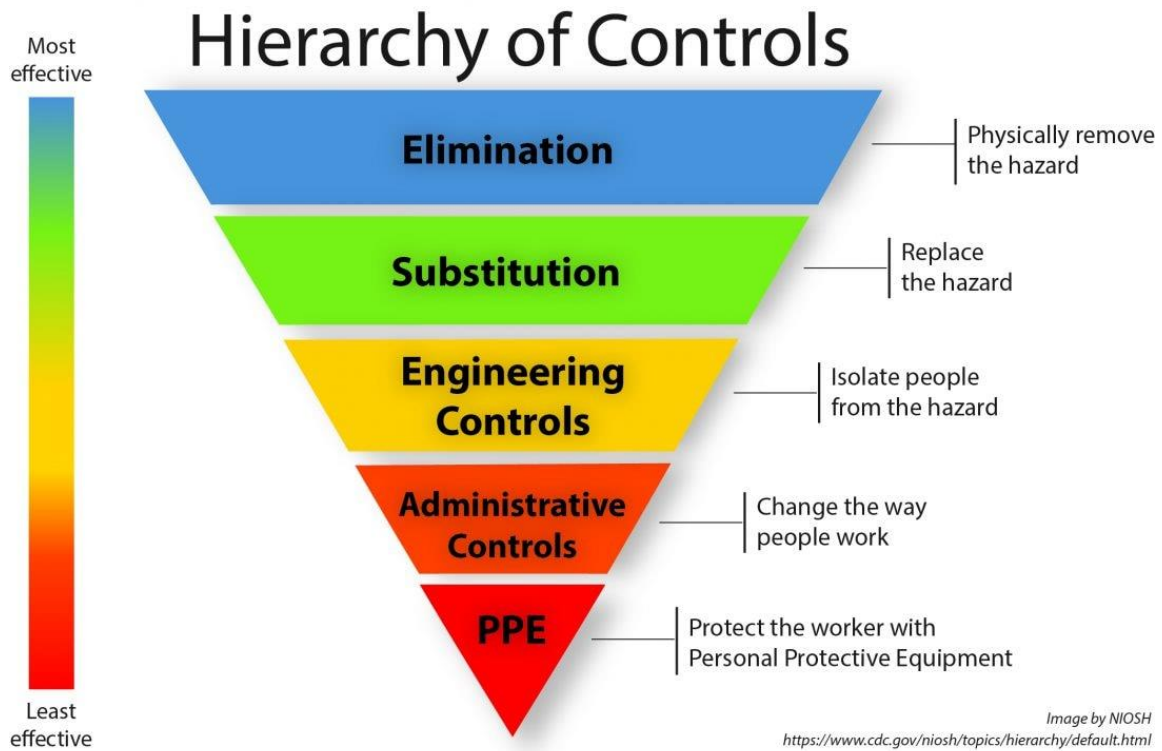
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Yoon, H., & Smith, J. L. (1999). Psychophysical and physiological study of one-handed and two-handed combined tasks. *International Journal of Industrial Ergonomics*, 24(1), 49–60. [https://doi.org/10.1016/S0169-8141\(98\)00087-0](https://doi.org/10.1016/S0169-8141(98)00087-0)

Zhang, X., & Chaffin, D. (2005). *Digital human modeling for computer-aided ergonomics*. <https://doi.org/10.1201/9781420003642-14>

## Appendices

### Appendix A: Hierarchy of Controls



# Appendix B: Screening Questionnaire

**Musculoskeletal Discomfort Form** (Based on the Nordic Questionnaire (Kourinka et al. 1987))

**Participant ID** \_\_\_\_\_

## How to answer the questionnaire:

**Picture:** In this picture you can see the approximate position of the parts of the body referred to in the table. Limits are not sharply defined, and certain parts overlap. You should decide for yourself in which part you have or have had your trouble (if any).

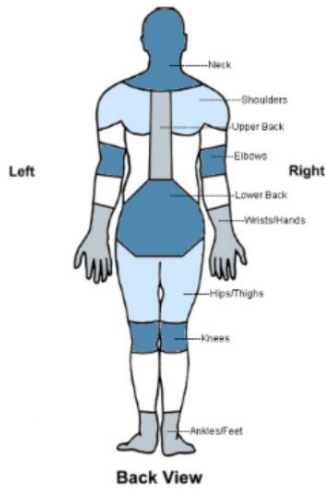


**Table:** Please answer by putting an "X" in the appropriate box - one "X" for each question. You may be in doubt as to how to answer, but please do your best anyway. Note that column 1 of the questionnaire is to be answered even if you have never had trouble in any part of your body; columns 2 and 3 are to be answered if you answered yes in column 1.

| To be answered by everyone                                                                                                                                                                            | To be answered by those who have had trouble                                                                                                  |                                                          |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------|
| Have you at any time during the last 12 months had trouble (ache, pain, discomfort, numbness) in:                                                                                                     | Have you at any time during the last 12 months been prevented from doing your normal work (at home or away from home) because of the trouble? | Have you had trouble at any time during the last 7 days? |
| <b>Neck</b><br><input type="checkbox"/> No <input type="checkbox"/> Yes                                                                                                                               | <input type="checkbox"/> No <input type="checkbox"/> Yes                                                                                      | <input type="checkbox"/> No <input type="checkbox"/> Yes |
| <b>Shoulders</b><br><input type="checkbox"/> No <input type="checkbox"/> Yes, right shoulder<br><input type="checkbox"/> Yes, left shoulder<br><input type="checkbox"/> Yes, both shoulders           | <input type="checkbox"/> No <input type="checkbox"/> Yes                                                                                      | <input type="checkbox"/> No <input type="checkbox"/> Yes |
| <b>Elbows</b><br><input type="checkbox"/> No <input type="checkbox"/> Yes, right elbow<br><input type="checkbox"/> Yes, left elbow<br><input type="checkbox"/> Yes, both elbows                       | <input type="checkbox"/> No <input type="checkbox"/> Yes                                                                                      | <input type="checkbox"/> No <input type="checkbox"/> Yes |
| <b>Wrists/Hands</b><br><input type="checkbox"/> No <input type="checkbox"/> Yes, right wrist/hand<br><input type="checkbox"/> Yes, left wrist/hand<br><input type="checkbox"/> Yes, both wrists/hands | <input type="checkbox"/> No <input type="checkbox"/> Yes                                                                                      | <input type="checkbox"/> No <input type="checkbox"/> Yes |
| <b>Upper Back</b><br><input type="checkbox"/> No <input type="checkbox"/> Yes                                                                                                                         | <input type="checkbox"/> No <input type="checkbox"/> Yes                                                                                      | <input type="checkbox"/> No <input type="checkbox"/> Yes |
| <b>Lower Back (small of back)</b><br><input type="checkbox"/> No <input type="checkbox"/> Yes                                                                                                         | <input type="checkbox"/> No <input type="checkbox"/> Yes                                                                                      | <input type="checkbox"/> No <input type="checkbox"/> Yes |
| <b>One or Both Hips/Thighs</b><br><input type="checkbox"/> No <input type="checkbox"/> Yes                                                                                                            | <input type="checkbox"/> No <input type="checkbox"/> Yes                                                                                      | <input type="checkbox"/> No <input type="checkbox"/> Yes |
| <b>One or Both Knees</b><br><input type="checkbox"/> No <input type="checkbox"/> Yes                                                                                                                  | <input type="checkbox"/> No <input type="checkbox"/> Yes                                                                                      | <input type="checkbox"/> No <input type="checkbox"/> Yes |
| <b>One or Both Ankles/Feet</b><br><input type="checkbox"/> No <input type="checkbox"/> Yes                                                                                                            | <input type="checkbox"/> No <input type="checkbox"/> Yes                                                                                      | <input type="checkbox"/> No <input type="checkbox"/> Yes |

## Appendix C: Participant Demographics Form

1) Participant ID \_\_\_\_\_

2) Age: \_\_\_\_\_

3) Sex assigned at birth: Female/ Male

4) Height: \_\_\_\_\_ ft/inch or m

5) Body mass: \_\_\_\_\_ lbs or kg

6) Handedness: (Left/ Right/ Both)

7) Program of Study: \_\_\_\_\_

8) Experience with Manual Material Handling (MMH) (None/ > 3months / > 6months / > 1 year)

Please specific the type of MMH if applicable \_\_\_\_\_

9) Please specify if you have received any MMH lifting training:

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# Appendix D: Edinburgh Handedness Inventory

## Writing

☐ Left Hand ☐ Right Hand

## Drawing

☐ Left hand ☐ Right hand

## Throwing

☐ Left hand ☐ Right hand

## Operating Scissors

☐ Left hand ☐ Right hand

## Using a Toothbrush

☐ Left hand ☐ Right hand

## Using a Knife (without Fork)

☐ Left hand ☐ Right hand

## Using a Spoon

☐ Left hand ☐ Right hand

## Using a Broom (upper hand)

☐ Left hand ☐ Right hand

## Striking/Light a Match

☐ Left hand ☐ Right hand

## Open the Lid of a box

☐ Left hand ☐ Right hand

## (Optional) Which Foot do you prefer to kick with?

☐ Left foot ☐ Right foot

## (Optional) Which eye do you use when using only one?

☐ Left eye ☐ Right eye

---

## Edinburgh Handedness Inventory

Thanks for submitting your response! Your handedness score is:

12

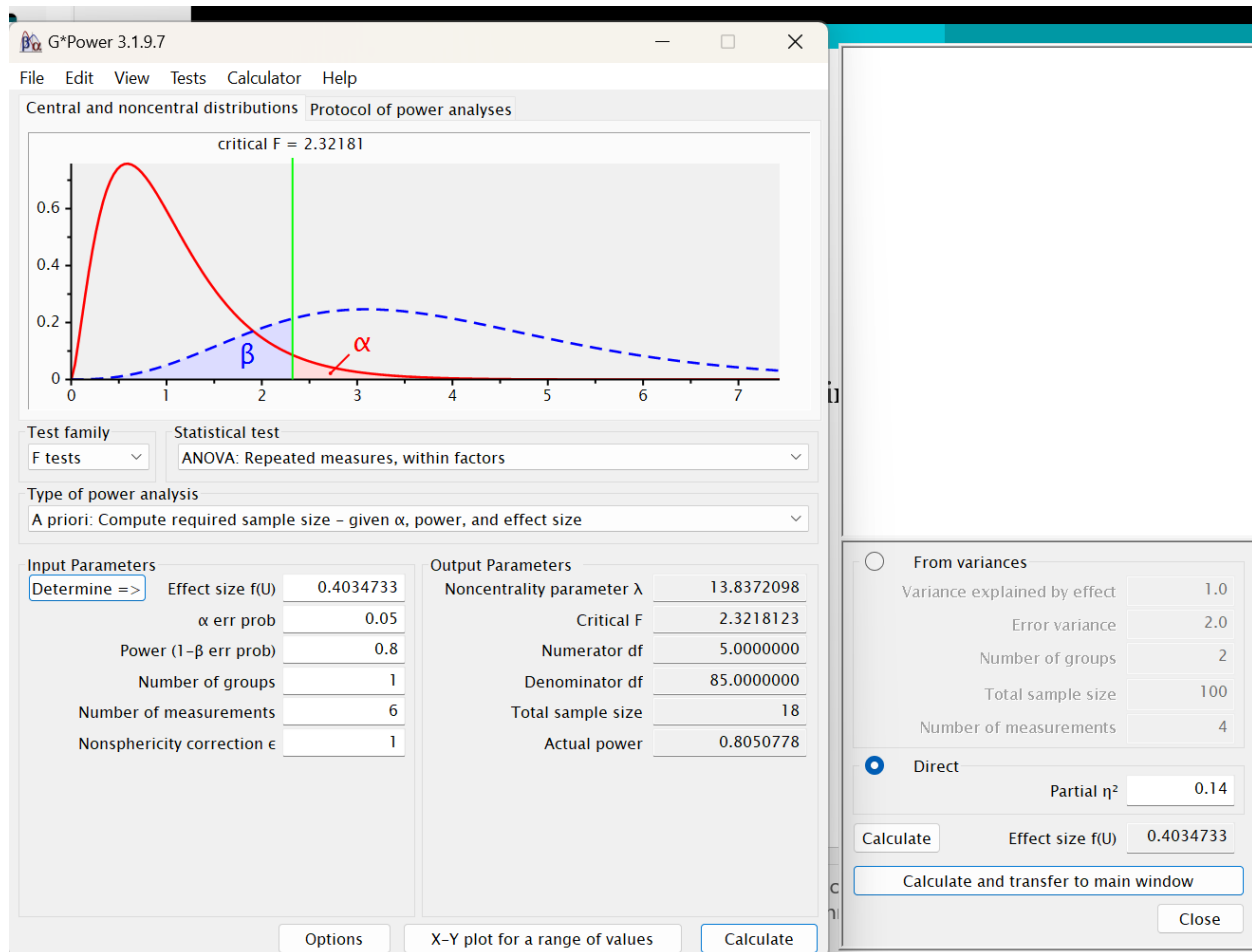
A score lower than Zero indicates that you are predominantly left-handed;  
a score larger than Zero indicates that you are predominantly right-handed.

**Thank you for taking part in this experiment!**

### References

- Oldfield, R.C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, 9, 97-113.
- Veale, J.F. (2014). Edinburgh Handedness Inventory - Short Form: A revised version based on confirmatory factor analysis. *Laterality*, 19, 164-177.

## Appendix E: Sample Size Calculation (Study One)



## **Appendix F: Verbal Instructions**

### **Study One:**

You will collapse/expand the dimension of the box until you perceive that it is the maximum box dimension that you can transfer with only one hand (dominant hand) safely and comfortably repeatedly throughout the day. You will either be grabbing the box from the top or from the front. Throughout the box transfer, you need to maintain five-points of contact with the box's cardboard surfaces, meaning that the thumb needs to be in contact with one side, and the other four fingers need to be in contact with the other side of the box. You will be transferring the box off the shelf onto the table standing behind you (1m away from the shelf), I will then reset the dimension of the box and place it back onto the shelf for your next adjustment and transfer. We will repeat these steps 60 times within the two hours we have.

### **Study Two:**

You will add/remove lead shots into or out of the box until you perceive that it is the maximum box mass that you can safely and comfortably transfer with only one hand (dominant hand) repeatedly throughout the day. You will either be grabbing the box from the top or from the front. Throughout the box transfer, you need to maintain five-points of contact with the box's cardboard surfaces, meaning that the thumb needs to be in contact with one side, and the other four fingers need to be in contact with the other side of the box. You will be transferring the box off the shelf onto the table standing behind you, I will determine the final mass of the box, then reset the starting condition of the box and place it back onto the shelf for your next mass adjustment and transfer. We will repeat these steps 40 times within the two hours we have.

## Appendix G: Sample Calculation for Grip Strength Relative to Population Norm

For the box not to slip off, grip force exerted must at least balance gravity

$$F_{\text{friction}} = F_{\text{gravity}}$$

$$\mu \cdot F_{\text{grip}} = m \cdot g$$

$$F_{\text{grip}} = \frac{m \cdot g}{\mu}$$

Since friction between hand and cardboard is 0.46 (Seo et al., 2009),  $\mu = 0.46$ .

Gravity:  $g = 9.81 \text{ m/s}^2$

Assuming the box is 3kg:  $m = 3\text{kg}$

$$F_{\text{grip}} = \frac{m \cdot g}{\mu} = \frac{3 \cdot 9.81}{0.46} \approx 63.98\text{N}$$

Assuming the participant is a 25 years old female, referring to normative grip strength reported by Trampisch et al. (2012) when measured at handle position 5 (Appendix J):

Normative grip strength = 22.6kg

Convert normative grip strength to Newtons =  $22.6\text{kg} \cdot 9.81 \approx 221.71\text{N}$

$$\text{Grip force relative to population norm} = \frac{F_{\text{grip}}}{F_{\text{norm}}} \cdot 100\% = \frac{63.98\text{N}}{221.71\text{N}} \cdot 100\% \approx 28.86\%$$

## Appendix H: Sample Calculation for Wrist Torque Relative to Population Norm

$$\tau = F \cdot d$$

where:

$\tau$  = rotational effect of the force around the wrist joint.

F = force applied by the hand to support the mass

d = moment arm OR perpendicular distance from the wrist joint to the line of action off F

Assuming the mass acts roughly through the middle of the hand, and hand length is 0.18m:

$$d = \frac{\text{hand length}}{2} = \frac{0.18m}{2} = 0.09m$$

Since force is the effect of gravity acting on the mass of the box, and assuming the box is 3kg:

$$F = m \cdot g = 3 \cdot 9.81m/s^2 \approx 29.43N$$

$$\tau = F \cdot d = 29.43N \cdot 0.09m \approx 2.65Nm$$

Assuming the participant is female and a top-grasped box transfer was performed, referring to normative wrist extension strength reported by La Delfa et al. (2015) (Appendix J):

Normative wrist extension strength = 4.07Nm

$$\text{Wrist torque relative to wrist extension strength} = \frac{2.65Nm}{4.07Nm} \cdot 100\% \approx 65.1\%$$

## Appendix I: Distribution of Outcome Measures as a Function of Hand Length and Stratified by Sex

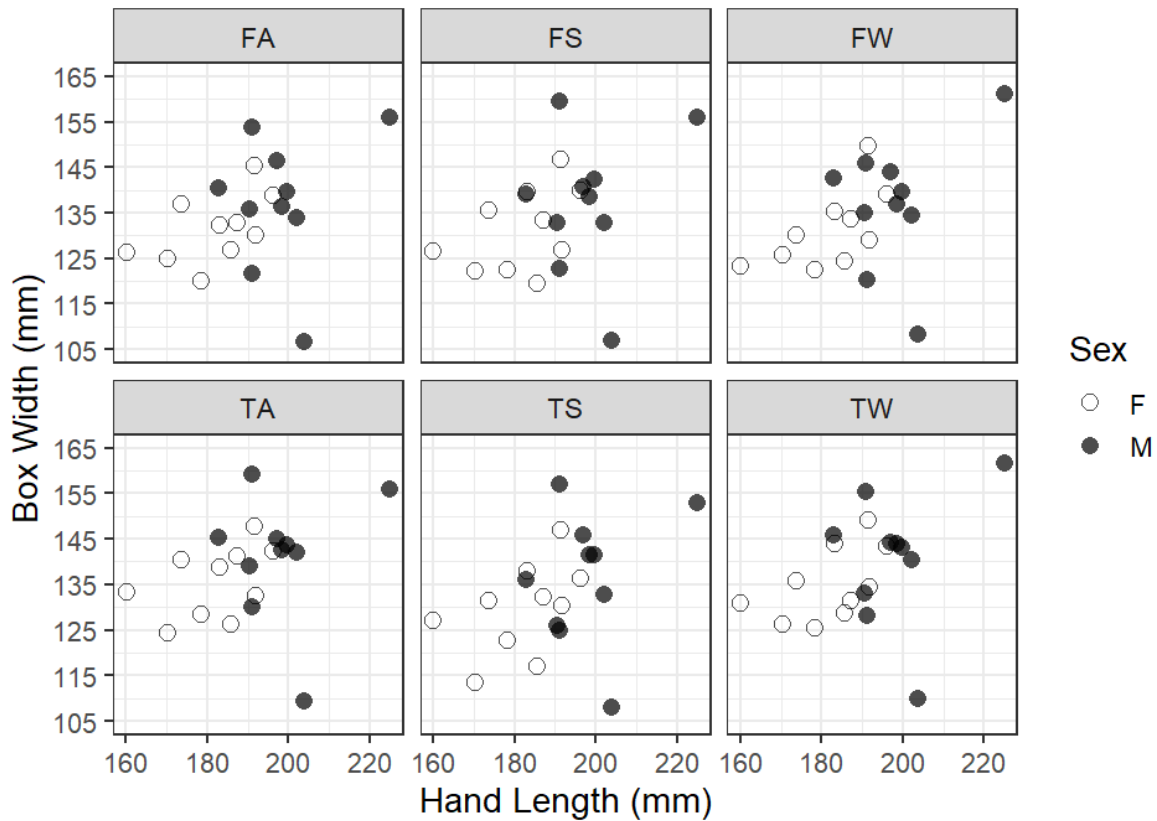


**Figure 1.** Distribution of perceived maximum box width as a function of hand length stratified by sex across 2 grip orientations (F-Front; T-Top) and 3 shelf heights (A-Ankle; S-Shoulder; W-Greater Trochanter).

### General observations:

- Participants' hand lengths generally ranged from 160mm to 225mm for Study One.
- Perceived maximum box width generally ranged from 105mm to 165mm.
- Males generally had larger hand lengths compared to females, but they had wider range of perceived maximum box width.
- The influence of hand length on perceived maximum box width was relatively smaller for Top-Ankle condition compared to the other conditions.

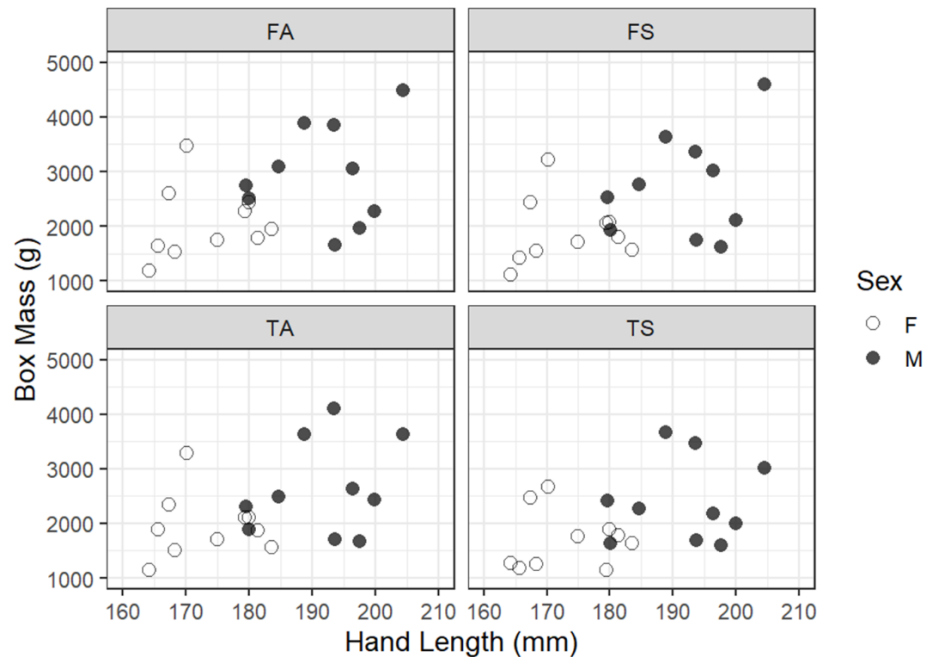


**Figure 2.** Distribution of perceived maximum box mass as a function of hand length stratified by sex across 2 grip orientations (F-Front; T-Top) and 2 shelf heights (A-Ankle; S-Shoulder).

General observations:

- Participants' hand lengths generally ranged from 160mm to 205mm for Study Two.
- Perceived maximum box mass generally ranged from 1000g to ~4500g when the box was set at maximum grip span determined from Study One.
- Males generally had higher perceived maximum box mass compared to females with larger spread of data points.
- The influence of hand length on perceived maximum box mass was relatively smaller for Top-Shoulder condition compared to the other conditions.

## Appendix J: Maximal Grip Strength and Wrist Torque Found from Previous Biomechanical Studies

**Table 1.** Maximal ( $\pm$  SD) hand grip strength in kg, determined using Jamar Dynamometer at 5 handle positions (1-narrowest; 5-widest) by Trampisch et al. (2012). Note that participants' data were normalized based on their sex and age matched data (highlighted in red below).

| Handle Position | Age (y)                          |                                  |                                  |                                  |                                  |                                  |
|-----------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
|                 | < 30                             |                                  | 30–39                            |                                  | 40–49                            |                                  |
|                 | Women (n = 8)                    | Men (n = 5)                      | Women (n = 6)                    | Men (n = 5)                      | Women (n = 7)                    | Men (n = 3)                      |
| 1               | 29.1( $\pm$ 5.4)                 | 45.8( $\pm$ 9.4)                 | 35.7( $\pm$ 2.3)                 | 39.0( $\pm$ 7.0)                 | 32.6( $\pm$ 2.2)                 | 35.3( $\pm$ 5.7)                 |
| 2               | <b>33.9(<math>\pm</math>4.3)</b> | 54.2( $\pm$ 7.2)                 | <b>38.2(<math>\pm</math>3.1)</b> | <b>53.8(<math>\pm</math>8.9)</b> | <b>36.3(<math>\pm</math>4.3)</b> | <b>48.0(<math>\pm</math>6.2)</b> |
| 3               | 31.9( $\pm$ 4.2)                 | <b>56.4(<math>\pm</math>8.4)</b> | 35.8( $\pm$ 3.7)                 | 53.4( $\pm$ 8.9)                 | 35.6( $\pm$ 4.4)                 | 46.0( $\pm$ 7.2)                 |
| 4               | 27.6( $\pm$ 3.5)                 | 51.8( $\pm$ 11.1)                | 30.7( $\pm$ 3.2)                 | 48.0( $\pm$ 6.9)                 | 30.9( $\pm$ 5.0)                 | 41.3( $\pm$ 6.1)                 |
| 5               | 22.6( $\pm$ 4.0)                 | 46.4( $\pm$ 7.4)                 | 27.0( $\pm$ 3.8)                 | 43.0( $\pm$ 8.7)                 | 26.1( $\pm$ 4.1)                 | 33.7( $\pm$ 5.0)                 |

**Table 2.** Maximal ( $\pm$  SD) wrist extension and radial deviation torques in Nm in 24 young, healthy university-aged participants, reported by La Delfa et al. (2015). Note that participants' data were normalized based on their sex matched data (highlighted in red below) assuming neutral forearm posture.

| Sex    | Forearm rotation | Exertion direction (N.m) |                  |                 |                  |
|--------|------------------|--------------------------|------------------|-----------------|------------------|
|        |                  | Extension                | Flexion          | Rad. Dev.       | Uln. Dev.        |
| Female | Pronated         | 3.71 $\pm$ 1.25          | 4.62 $\pm$ 1.57  | 4.51 $\pm$ 1.76 | 3.95 $\pm$ 1.57  |
|        | Neutral          | 4.07 $\pm$ 1.45          | 5.68 $\pm$ 1.60  | 3.60 $\pm$ 1.35 | 4.52 $\pm$ 1.69  |
|        | Supinated        | 2.71 $\pm$ 0.89          | 4.14 $\pm$ 1.19  | 3.56 $\pm$ 1.37 | 3.97 $\pm$ 1.64  |
| Male   | Pronated         | 8.82 $\pm$ 2.07          | 12.28 $\pm$ 2.49 | 9.39 $\pm$ 1.52 | 5.86 $\pm$ 0.77  |
|        | Neutral          | 5.99 $\pm$ 0.85          | 12.29 $\pm$ 1.09 | 8.08 $\pm$ 2.04 | 10.66 $\pm$ 3.46 |
|        | Supinated        | 6.52 $\pm$ 1.56          | 10.10 $\pm$ 1.84 | 5.41 $\pm$ 0.77 | 7.77 $\pm$ 2.02  |