MEDIATORS OF DECISION MAKING IN ACTION PLANNING

MEDIATORS OF DECISION MAKING IN ACTION PLANNING: ASSESSING THE FUNCTIONAL COSTS OF ALTERNATIVE MOVEMENT STRATEGIES

By
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ABSTRACT

The human motor system is constantly faced with decisions about how to choose a path when navigating our environment. These types of decisions occur rapidly and constantly, from initial movement planning, through movement execution, to completion. With infinite ways to complete any given task, the central nervous system generally, and motor control systems specifically, must somehow “decide” the best way to do this while taking into account physiological and environmental constraints. In addition, these movement choices must consider the feasibility and efficiency of all movement alternatives. For example, when deciding between paths that vary in reach distance and walking distance, the path with the shorter reach distance is more likely to be chosen, as reaching is deemed to be ~10x more costly than walking a given distance (Rosenbaum et al., 2011; Rosenbaum, 2012). It is not clear, however, how much more costly the non-chosen path is, compared to the chosen path, and what factors are mediating these decisions. Thus, the purpose of this thesis was to investigate potential underlying non-cognitive mediators of behavioural decisions involved with posture selection during tasks that occur within a constrained task environment, by quantifying the biomechanical mechanisms that may be driving these decisions. Chapter 2 replicated and extended upon the work of Rosenbaum et al. (2011) by recording whole-body motion capture during a bucket transfer task. This study was the first to look at the loading of the shoulder joint and trunk during the reaching and walking decision paradigm, comparing joint loading in the chosen versus unchosen paths.

In Chapter 3, participants made decisions between movements with seemingly similar functional distances, in a four-choice reaching and walking paradigm. Behavioural outcomes suggest that the decision-making process reflects spatial coding of the movement goal that is backwards planned from the task sub-goal. Chapter 4 explored how perceived costs of multiple task variables are prioritized and integrated into action planning. Here, participants prioritized decreased reach distance over bearing an increased load. Collectively, this thesis provides evidence that bottom-up processes, namely the biomechanics of the shoulder and trunk, exert influence on cognitive decision-making and action planning, as reflected in decreased joint loading in chosen versus unchosen paths.

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Cheers.

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DECLARATION OF ACADEMIC ACHIEVEMENT

This document contains five chapters of original research conducted by the primary author, Jessica Anne Marie Cappelletto, as part of her Ph.D. studies. Jessica Cappelletto made significant contributions to all aspects of this dissertation, including the conceptualization of the research questions, design of the empirical research studies, preparation and submission of the ethics application, collection of experimental data, processing and analysis of experimental data, interpretation of the results, and preparation of this manuscript. Dr. James Lyons, the Ph.D. supervisor made contributions to substantially support this process, including involvement in the study conceptualization and design, interpretation of the results, the editing of this dissertation document, and continued guidance and support. The supervisory committee consisted of Dr. Michael Carter, Dr. Aimee Nelson, and Dr. Jim Potvin. The committee was continuously involved in the oversight of the research progress through annual meetings and discussions of the research ideas, study design, and interpretation of results. Stevie Foglia, Anthony Sitas, Claire Tuckey, and Noah Erskine provided assistance with the data collection and/or data processing of the experiments in Chapters 3 and 4.

CHAPTER 1

GENERAL INTRODUCTION

How humans choose the postures and actions that are used to carry out behavioural goals is a widely researched topic in the areas of biomechanics, cognitive psychology, and motor behaviour and control. One of the major challenges that we face in choosing one action over another, when many of these actions would serve the purpose of answering the movement goal, lies in the seemingly infinite options that are available to us. Although Lashley (1933) was likely the first researcher to directly and formally assess these multiple movement redundancies (or motor equivalences), it was Bernstein (1967) who suggested that these many movement options can actually be considered a *problem* that must be resolved by the motor system. Bernstein's conceptualization of this "Degrees of Freedom Problem" essentially holds that the mechanical drivers of movement (e.g., single muscles) do not act in isolation. Rather, many "nervous centers" must communicate and cooperate to make complex movements possible. Typically, as experiences with movement increase, these nervous centers coordinate to arrive at the most efficient movement option given the immediate movement constraints. In this way, the many initial degrees of freedom are constrained such that an appropriate combination of movement synergies is achieved. If we consider the degrees of freedom problem introduced by Bernstein (1967), the human motor system has the capability to perform the same task in multiple ways, with infinite combinations of joint angles, muscle forces, and paths taken to achieve that goal.

At a more macro scale, we are constantly faced with similar decisions about how to choose the best movement path to carry out our goals as we navigate our surroundings. These decisions occur rapidly and frequently, from initial movement planning, through movement execution, and to movement completion. These movement choices must consider the feasibility and efficiency of all movement alternatives, account for the psychological and environmental constraints of the task, as well as the physical constraints of the motor system. Despite the many choices that must be made by the motor system to complete a given action, evidence of stereotypical or emergent behaviours are revealed that presumably serve to optimize principles such as energy consumption (Sparrow and Newell, 1998), movement kinematics (Flash and Hogan, 1985; Hogan and Flash, 1987; Cruse, 1986; Cruse and Brewer, 1987), movement kinetics (Uno, Kawato & Suzuki, 1989), and/or sensory feedback control (Lepora & Pezzulo, 2015; Scott, 2002; Todorov & Jordan, 2002).

A common yet powerful example of one such emergent behaviour is what is now commonly referred to as the “End State Comfort Effect” (e.g., Rosenbaum, 1990). To illustrate this effect, imagine that you are tasked with picking up an inverted glass to fill it from a pitcher of water. In situations such as these, the actor will almost invariably grasp the glass with a pronated hand posture (uncomfortable) to flip it over with a supinated posture (comfortable) so that liquid can be poured inside. The reverse (initial supinated grip to pronated end-state grip) is seldom, if ever, observed. The theory behind why this stereotypical behaviour emerges postulates that actions are planned to ensure maximum comfort and stability at the point in the sequence of movement where it is most required: at the later stages of the movement (Rosenbaum et al., 1990). Although the theory has since evolved to reflect the use of the comfortable posture during the segment of the task that requires the most accuracy (see Burgess et al., 2014, Hughes et al., 2012; Rosenbaum et al., 2006), the rationale behind it stands: these movements reflect higher-order anticipatory object-centered planning (Haggard, 1998; Rosenbaum et al., 2012).

This abstract notion of "comfort" has generally been used to describe how the functional constraints of the motor system may govern the observed behavioural outputs. Postures that are typically classified as comfortable are ones that lie around the midpoint of a joint's range of motion, while uncomfortable postures approach the extremes. The end state comfort effect, and comfortable postures in general, allow for optimization of the speed and precision of movements in these postures (Rosenbaum, van Heugten, & Caldwell, 1996). While effort has been made to operationally define this notion of comfort as described through the mid-point of the joint range of motion, there is a need to further analyze this notion of comfort with objective, measurable outcomes (i.e., those typically employed in functional ergonomics research). To that end, our lab has recently been working to quantify why these observed behavioural patterns emerge by investigating the relationship between maximum voluntary force production and perceived discomfort ratings in thumb-up and thumb down grip postures. A negative relation between maximal force output and discomfort ratings exists, with thumb-down postures yielding lower force output and higher discomfort ratings than thumb-up postures, suggesting that this behavioural phenomenon is driven by functional mechanical advantages (Burgess et al., 2016).

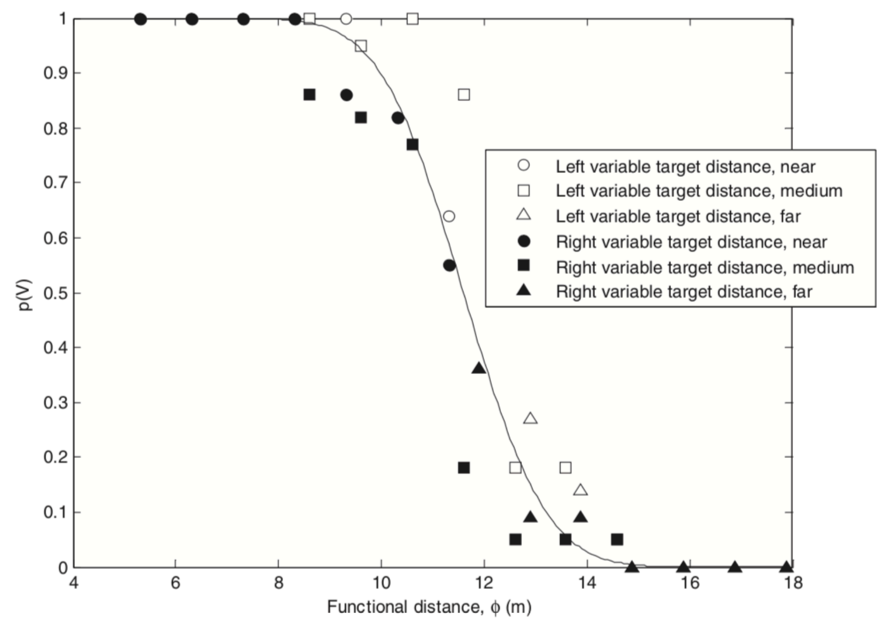
Although these stereotyped behaviours occur often, there is evidence that a movement plan will sometimes be altered in favour of one that may provide additional benefits. For example, in a manufacturing setting such as an automotive assembly plant, workers often have to complete their task around an existing framework, navigating through an encumbered environment to complete their job. In these instances, where the task is constrained by both the object they are assembling and the surrounding environment, the workers need to develop strategies that allow them to complete their task efficiently (i.e., behaviours can and do change as a function of time and place). There is well-documented evidence of humans employing postural and behavioural adaptation strategies within an environment with imposed constraints to take advantage of such mechanical factors, thereby making the task feel easier (Cappelletto, Smets, Liebregts, & Potvin, 2017; Jones, Kirshweng, Armstrong, & Reed, 2008). Specifically, automotive assembly workers frequently use external support behaviours (via leaning and bracing) to increase the force-generating capability of the task hand as well as maintenance of balance when a large arm reach distance is required

(Jones et al., 2013; Cappelletto, 2013). These adaptive behaviours also serve to decrease the demands at the trunk and the shoulder, when compared to performing the tasks in the absence of external support strategies, and are therefore chosen to minimize joint stress during the task (Cappelletto & Potvin, 2014; Fewster and Potvin, 2018; Kingma & van Dieen, 2004; Howard et al., 2012; Ferguson et al., 2002; Liebregts 2014).

Although tasks such as reaching movements of the arm and human locomotion are well studied, they are often assessed in isolation and independent of each other; yet, able-bodied individuals perform seamlessly coordinated reaching and walking movements every single day. Actions typical of the workplace, such as a manufacturing worker retrieving a part from a supply bin to transport it to a workstation, also occur with great frequency in fundamental activities of daily living. For example, imagine grabbing your car keys while rushing out the door, selecting items for purchase while shopping in a store, or preparing your dinner plate at a buffet restaurant. In each of these examples, covert movement decisions must be continuously made in order to efficiently coordinate the many moving anatomical parts into a single, cohesive action unit. The body of literature studying how the basic motions of reaching, grasping, and locomotion are integrated however, is relatively thin when compared to the study of these movements in isolation.

The aforementioned task examples all require coordinated reaching and walking movements that require a decision to be made between the amount of walking to be done and the amount of reaching to be done. For example, imagine (again) that you are at a buffet station that has different dishes available when approached from either side. You chose the side with the hamburgers, but you then realize you would also like a slice of pizza. To satisfy both cravings, you could either prepare your dinner from the side you are on before walking around to the other side for the pizza, or you could reach across the food, under the sneeze-guard, and grab a slice. Of course, this decision may rely on many factors, including how many slices of pizza are left for the taking or if there are other patrons around to judge you for reaching over the food, but at its heart this scenario requires a decision to be made between walking a greater distance or reaching a greater distance to achieve the same ultimate goal. This type of decision, essentially a trade-off between reaching and walking, has been studied in a recent line of behavioural experiments by Rosenbaum and colleagues (Potts, Callahan-Flintoft, & Rosenbaum, 2018; Potts, Pastel, & Rosenbaum, 2018; Rosenbaum, 2008; Rosenbaum, Brach, & Semenov, 2011; Rosenbaum, Gong, & Potts, 2014; Rosenbaum & Sauerberger, 2019; Rosenbaum, 2012). In these studies, whether a person will increase their reaching distance in order to minimize distance travelled by walking or decrease their reach length in favor of a longer walking path is the main question of interest. Their research provides valuable insight into how alternative paths involving multi-modal movement costs are evaluated and chosen and is discussed below.

Rosenbaum's group (Rosenbaum, 2008; Rosenbaum, Brach, & Semenov, 2011) investigated the trade-off between walking and reaching when retrieving a load and placing it at a target destination, using a two-alternative forced choice bucket transfer task. Their experiments consisted of a load, placed either on the right, middle, or left of a table, and target platforms on either the right or left side of the table. Given the starting position of the load, participants had to decide whether they would choose to complete the task of retrieving the load and placing it on the corresponding target platform via the path to the right of the table or to the left of the table. From this relatively simple yet elegant design, a distribution was created which gave the probability of selecting a movement path, given the start location of the bucket (Figure 1.1). Specifically, the probability of proceeding along a particular movement path decreased as the functional distance of that path increased (Rosenbaum, 2008, Rosenbaum et al., 2011). Here, functional distance refers to the summation of the length travelled by walking and the distance reached by the hand, both in metres. This result also held true when participants were asked to make a path choice based on photographs, and not physically perform the movements (Rosenbaum, 2012).



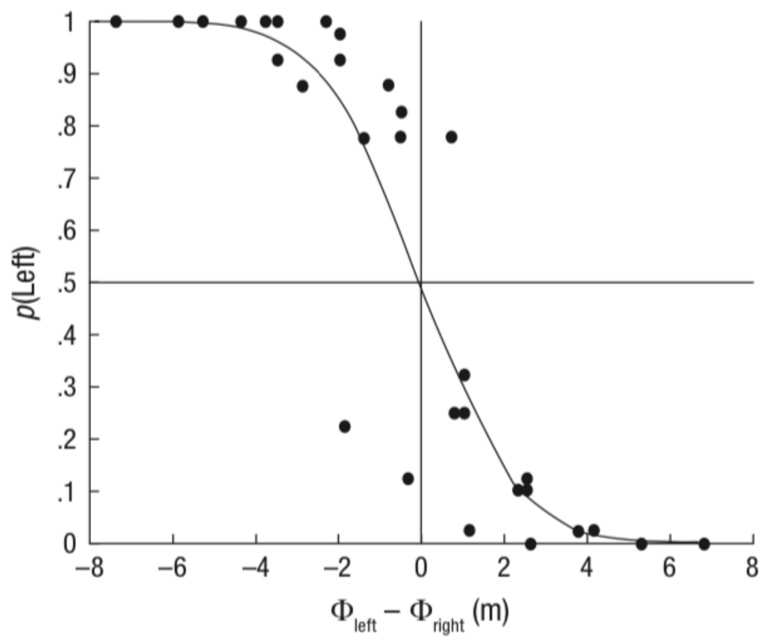


Figure 1.1: Path choice as a function of task functional distance. Note that as the functional distance (or difference between functional distances) increases, the probability of choosing that path decreases. Top: Figure 3 from Rosenbaum et al. (2011), page 135. Bottom: Figure 4 from Rosenbaum (2012), page 858.

Functional distance in those studies (Rosenbaum et al., 2011; Rosenbaum, 2012) was estimated by applying a coefficient to the reaching term. This coefficient was determined through an iterative process which minimized the sum of squared deviations between the observational outcomes and a model represented by one minus the cumulative density function of the normal distribution centered at zero. A coefficient of 10.2 (Rosenbaum et al, 2011) and 11.3 (Rosenbaum 2012) were determined to the reaching terms in their respective experiments; thus, reaching was deemed to be more costly than walking, leading to the avoidance of this behaviour wherever possible. Rosenbaum (2011) was the first to link this type of cognitive psychology to behavioural ecology by using distance travelled as a “common currency” for determining the cost of an action. It was hypothesized that as functional distance increased, so too would reaction time (RT), as the mechanism governing path choice was likely a serial simulation of both actions which would result in the ultimate selection of the easier or more favourable path (Rosenbaum, 2012). The choice RT data obtained in that study led to the rejection of the serial simulation hypothesis in favour of the differential selection method hypothesis (Figure 1.2). The differential selection method hypothesis states that when the paths differ in functional distance, it is the differences between path costs that are evaluated in order to choose the most efficient path, and not the entirety of both paths. A large path-differential leads to a faster RT (i.e., when there is a clear winner), and paths that are similar in functional distance require longer processing times, accounting for the inverted-U shape of the curves.

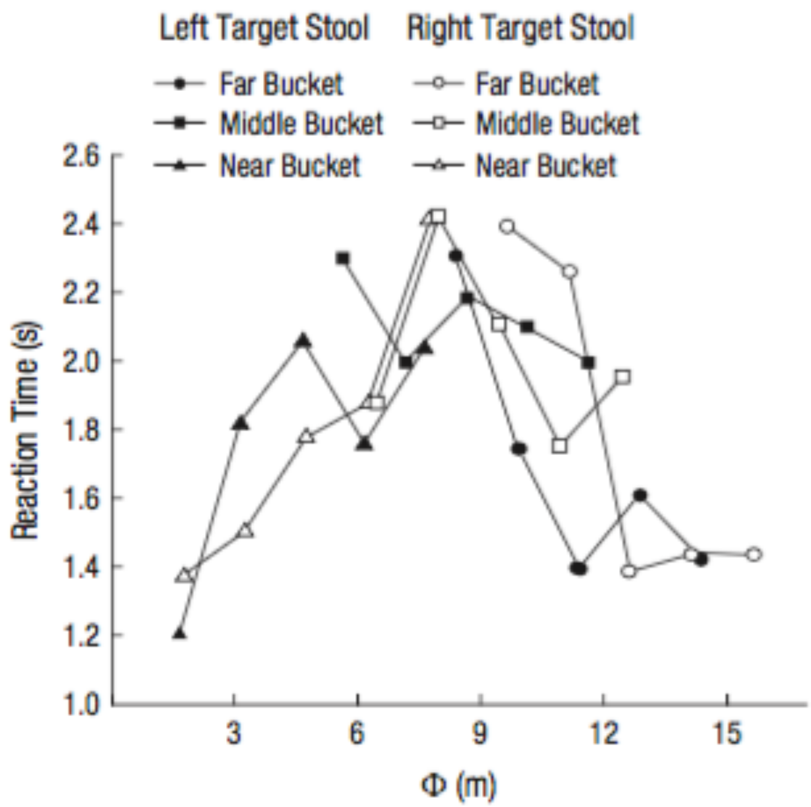


Figure 1.2: Choice reaction time data plotted against functional distance (Φ) in m for each configuration. Inverted-U shape indicates increased processing time is necessary for trials with intermediate functional distances. Figure 6 from Rosenbaum (2012), page 859.

Moreover, Rosenbaum's research group discovered another behavioural phenomenon associated with the reaching and walking trade-off they termed pre-crastination. Pre-crastination is defined here as the observed tendency to complete the sub-goal of the task as soon as possible, regardless of the resulting increase in energy expenditure. More specifically, when given a choice between picking up a load after walking four feet and carrying it 12 feet or picking up a load after eight feet and carrying it eight feet, participants were more likely to choose the first option (Rosenbaum et al., 2014). Even though the total path distance is 16 feet in both scenarios, minimizing the approach distance was preferred, despite being somewhat counterintuitive, since this would require the load to be carried longer, and is therefore less energetically efficient than carrying that same load for a shorter duration. Through a series of experiments, a number of hypotheses for why this phenomenon occurred were tested and subsequently rejected, including: the earlier load was chosen to better coordinate an ipsilateral stance-grasp relationship; participants preferred to retrieve the load while walking more slowly (i.e., before reaching peak velocity) and; the closer load better attracted the attention of the participants. Rosenbaum et al. (2014) therefore hypothesized that the pre-crastination effect reflects a behaviour that serves to decrease working memory during a task. This explanation is quite consistent with traditional theories of decision making that posit the less effortful of two options (including the mental effort of information processing) will consistently be chosen (Hull, 1943; Kool, McGuire, Rosen, & Botvinick, 2010). Interestingly, however, when the cost of the load retrieval increased (e.g. the load choices were of different magnitudes or the reach distances varied), the effect diminished such that the preference for carrying a lighter load was prioritized over the pre-crastination behaviour (Potts, Callahan-Flintoft, et al., 2018; Rosenbaum et al., 2014). This suggests that minimizing the physical demand imposed by the increased cost is prioritized over the need to minimize the cognitive effort associated with the working memory hypothesis.

Although the work exploring reaching and walking catalogues aspects of the task environment into the movement process and provides naturalistic evidence for how decisions are made between alternative movement paths, more work is needed to explore and better understand the mechanistic underpinnings of these decisions. What about the reaching movement, specifically, is considered suboptimal to walking? This increased cost associated with reaching as compared to walking was proposed to arise from the need to displace the trunk away from an upright, standing posture when retrieving a load placed at a longer reach distance (Rosenbaum et al., 2011). Similar to the end state comfort literature, this rationale attributes the observed behavioural outcomes to the need to minimize the costs of discomfort associated with extreme joint angles. It would be beneficial, then, to explore the locus of comfort/discomfort as a mediator of behaviour and investigate methods of quantifying the relationship between functional, mechanical constraints and behavioural decision making. Perhaps there exists a boundary or limit where, when surpassed, a fundamentally new behaviour emerges (e.g. as seen in the shift from walk to run as locomotor velocity increases). While the main research questions in this field have pertained to the observation and identification of the decision outcomes made within a particular movement environment, it would be pertinent to investigate mechanisms within the motor system that may be driving these decisions.

There is compelling evidence that such an approach is warranted. For example, when choosing between possible targets during a unimanual reaching movement, the biomechanics of the arm plays an important role in decision-making (Cos, Bélanger, & Cisek, 2011; Cos, Duque, & Cisek, 2014; Cos, Medleg, & Cisek, 2012; Marcos, Cos, Cisek, Girard, & Verschure, 2013; Marcos, Cos, Girard, & Verschure, 2015). Predictions of biomechanical consequences of a motor action are used to determine the less effortful, and therefore less costly, sequence to be performed (Cos et al., 2011). Indeed, in their embodied choice framework, Lepora & Pezzulo (2015) suggest the causal influence of movement dynamics on cognitive decision making. This framework incorporates feedback gained regarding the motor costs of actions into the decision-making process in an online fashion, making advances over serial and parallel models which require costs obtained from action priors to inform a decision. While these costs are often considered in the sense of metabolic or energetic cost, recent evidence suggests that it is the subjective perception of effort, rather than the metabolic cost to the system, that is used as the basis of these decisions (Cos, 2017; Morel, Ulbrich, & Gail, 2017). Additionally, in situations where the physical demands of the task are equal, decision-making will favour the task with decreased cognitive demand (Kool et al., 2010). To the best of my knowledge, the consideration of joint biomechanics in the decision-making process during a walking and reaching task has not yet been studied. It is logical to assume that these same principles hold true when the complexity of the task increases from that of a seated reaching movement to a coordinated walking and reaching task, as the co-ordination of arm movements of reaches made during locomotion and during stationary conditions have revealed similar global trajectories (Marteniuk & Bertram, 2001).

Further, investigations of worker behaviour during manual materials handling tasks provide additional evidence to support the rationale for considering biomechanical factors as predictors of reaching and walking behaviours. During a lifting task, participants displayed a preference to reach a farther distance for a light (6 kg) load compared to a heavy (16 kg) load (Faber et al., 2007). Despite the increase lifting distance, and consequently larger resulting moment arm, the modified behavioural strategy still led to reductions in net trunk moment in the lower load conditions (Faber et al., 2007). Moreover, while Konemann et al. (2015) saw no effect of object weight on the reaching distance when participants performed a pick and place task, participants displayed an overall preference to reach, rather than walk, to retrieve items from a bin, contrary to the reaching and walking studies from Rosenbaum's group. Thus, altering task variables such as load or frequency may lead to a redistribution of the costs associated with reaching and walking behaviors.

Therefore, to move toward predicting these observed stereotypical behavioural outcomes, we must better understand the factors that drive the underlying decision-making processes, especially when costs are seemingly similar. It is intuitive to identify the "easiest" or "most comfortable" path or behaviour when the choices are notably different. However, it becomes less clear to identify what behaviour will be chosen among options with comparable costs. This thesis seeks to identify if, and which, functional constraints underlie these choices.

1.1 - Thesis Overview

The primary objective of this thesis is to identify potential underlying functional mediators of behavioural decisions involved with posture selection during exertions that occur within a constrained task environment by quantifying the biomechanical mechanisms that may be driving these decisions. In general terms, I am interested in attempting to identify if (and which) biomechanical constraints act as cognitive “triggers” for wholesale changes in behaviours. This research question is centered about identifying and investigating the factors that drive hierarchical decision-making when selecting actions for task performance.

Chapter 2 of this thesis extends the work of Rosenbaum’s group by recording whole-body motion capture during a bucket transfer task, using methods outlined in, and consistent with, Rosenbaum et al. (2011) and Rosenbaum (2012). This study is, to the best of our knowledge, the first to look at the loading of the shoulder joint and trunk during this type of reaching and walking decision making paradigm by comparing joint loading in the chosen versus non-chosen paths. In Chapter 3, participants make decisions between movements with equal walking distances in a four-choice reaching and walking paradigm. Behavioural outcomes suggest that the decision-making process reflects spatial coding of the movement goal that is backwards planned from the task sub-goal. Chapter 4 explores how perceived costs of multiple task variables are prioritized and integrated into action planning. Here, participants prioritized decreased reach distance over bearing an increased load. Collectively, this thesis provides evidence that Bottom-Up processes involving the biomechanics of the shoulder and trunk exert influence on the typically considered “Top-Down” cognitive processes informing decision-making in planning actions.

CHAPTER 2

QUANTIFYING THE BIOMECHANICAL COSTS USED TO MAKE BEHAVIOURAL DECISIONS WHEN CHOOSING BETWEEN ACTION PLANS

2.1 – Abstract

The purpose of this study is to examine the trade-off between reaching and walking by quantifying biomechanical factors used to decide between two potential action plans. In terms of functional distance travelled, reaching is deemed to be more costly than walking (Rosenbaum et al., 2011; Rosenbaum, 2012). It is less clear, however, how much *more* costly reaching is than walking when directly comparing chosen and unchosen paths, and how these costs are represented within the CNS. This study expands upon Rosenbaum et al.'s (2011; Rosenbaum, 2012) work by presenting participants with each trial condition twice thereby allowing for the direct comparison of the demands of the chosen path versus non-chosen path. The results provide evidence that biomechanical factors, such as joint loading, can drive cognitive decision making when choosing postures for action.

2.2 – INTRODUCTION

When navigating through our environment to complete activities of daily living, we are faced with many decisions regarding how to perform a given task. These types of decisions occur rapidly and constantly, from initial movement planning, through movement execution, to completion. With infinite ways to complete any given task, the central nervous system generally, and motor control systems specifically, must somehow "decide" the best way to do this while taking into account physiological and environmental constraints. In addition, these movement choices take into account the feasibility and efficiency of all movement alternatives. Typically, motor driven (and cognitive) models of movement planning are informed by the constraints imposed on movement by the task itself and the environment in which the task unfolds whereas traditional ergonomic models of movement typically consider the constraints imposed by an individual's personal physiology/anthropometry, mechanics and posture. Currently, the bulk of the literature exploring these issues assesses these constraints in isolation. We suggest that there is a need to consider more fully the *interactions* between the individual biomechanical properties of the actor and the cognitive processes of decision-making that combine to result in a given observable movement outcome.

For example, research in motor behaviour has investigated when an action plan will be abandoned for one that is deemed to be less costly. The primary question of interest in this work is whether/when a person will increase their reaching distance in order to minimize distance travelled by walking (or conversely, decrease their reach length in favor of a longer walking path). While this research provides insight into how alternative movement paths are evaluated and chosen, the main outcomes in these studies have been primarily observational in nature and, although the authors offer compelling theories as to why these decisions are being made, they do not *directly* assess, at a level of anatomical or mechanical function, what makes a decision more or less costly.

Rosenbaum et al. (2011; Rosenbaum, 2008; 2012) investigated the trade-off between walking distance and reaching distance when retrieving a load and placing it at a target destination using a bucket transfer task. Participants made decisions about their preferred walking path upon viewing the positioning of a load on a table and the path distances to target platforms, which varied in distance between trials. Participants had to decide whether they would complete the task via the path to the right of the table, or to the left of the table, based on the environmental information. Their results indicate that the probability of proceeding along a particular path decreased as the functional distance of that path increased (Rosenbaum et al., 2011; Rosenbaum, 2012)[1].

Rosenbaum et al. (2011) thus propose that when the paths differ in functional distance, the differences between the "costs" of the paths are evaluated in order to choose the most efficient path. When functional distances are similar, however, more complex comparisons must be made. This research implies that reaching is

[1] In this context, functional distance refers to the summation of the distance travelled by walking and the distance reached by the hand, in metres.

deemed more costly than walking a given distance thereby leading to the avoidance of this behaviour wherever possible (Rosenbaum 2008; 2012; Rosenbaum et al., 2011). Rosenbaum's group was able to link this type of cognitive psychology to behavioural ecology by using distance travelled as a "common currency" for determining the cost of an action.

Although this theory catalogs aspects of the task environment into the movement process and gives evidence for how actions would be performed in these scenarios, it does not include any mechanical explanation as to why humans respond in such a manner. More to the point, *why* is the reaching movement classified as suboptimal in comparison to walking by the human motor system? The increased cost of reaching was suggested by Rosenbaum and colleagues to arise primarily from the need to generally displace the trunk away from an upright, standing posture in order to retrieve the load with a long reach (Rosenbaum et al., 2011). However, as the complexity of the possible movement paths increases, the cost analyses occurring at the cognitive level become less clear (i.e., when the functional distances are equal). The main research questions in this area have, at least to date, pertained to the identification and outcome of the decisions made within a particular movement environment, but not necessarily what is driving these decisions from a functional, mechanical constraints perspective.

The biomechanics of the arm has been shown to bias decision-making during reaching tasks (Cos et al., 2011, Cos et al., 2012, Cos et al., 2014). Predictions of biomechanical consequences of a motor action are used to determine the less effortful, and therefore less costly, sequence to be performed (Cos et al., 2011). Currently, in the reaching and walking literature, the consideration of biomechanics in the decision-making process during a coordinated bucket transfer task, has yet to be investigated.

To this end we aim, in this study, to replicate and expand upon Rosenbaum's group's original reaching and walking studies by including kinematic measures and biomechanical analyses. In terms of functional distance travelled, reaching is deemed to be more "costly" than walking by a factor of approximately 11 (Rosenbaum et al., 2011; Rosenbaum, 2012). It is not clear, however, how much more costly reaching is than walking when directly comparing the chosen and unchosen paths, and what the central nervous system uses to define these costs. Why is one path is chosen over another when discrepancies in functional distance are not apparent?

In this experiment, each participant is presented with each trial condition twice. They were allowed to choose their movement path upon the first task presentation and then they performed the task along the second (non-chosen) path during the second task presentation. With this design, the demands of the preferred choice path versus the non-chosen path can be directly compared, and differences in joint demands and functional distances can be analyzed to determine the increased cost incurred in the non-chosen target alternative.

It is hypothesized that, consistent with the reaching and walking literature (Rosenbaum 2008; 2012, Rosenbaum et al. (2011), participants would choose movement paths that primarily minimize reach distance. In addition, we hypothesize that the chosen paths will primarily minimize trunk and shoulder loading by choosing the path that minimizes postures requiring increased trunk flexion and lateral bending, thus having a lower total cost than the unchosen posture. These predictions are collectively based on psychophysical research suggesting that postures are chosen in such a way to minimize the total minimum perceived cost (Cruse et al., 1990). Moreover, as the difference between the functional distance of the path options increases, it is predicted that there will be a more pronounced difference in joint loading between the chosen and unchosen paths. The cumulative moment measures will give an indication of the biomechanical costs incurred throughout the duration of the trial and will likely provide insight into how decisions are made when the difference between functional distances of the path choices is minimal.

2.3 – METHOD

2.3.1 – Participants

Eleven university-aged females (25.13 $\pm$ 3.40 years) were recruited from the McMaster University population to participate in this study. All participants were right hand dominant, with a laterality index of 90 $\pm$ 7.4 (Edinburgh Handedness Inventory). All participants were free of any musculoskeletal disorders or symptoms for the 12 months prior to study involvement. All portions of this study were approved by, and conducted in accordance with, the McMaster University

Research Ethics Board (Appendix A). Prior to testing, participants were informed of the purpose, methods, and procedures involved in the data collection and provided written informed consent (Appendix B).

2.3.2 – Instrumentation and Data Acquisition

Similar to Rosenbaum et al. (2011), the experimental set-up consisted of a 1.5 x 0.75 x 0.77 m table, as well as two bar stools that were 0.62 m in height, with 32 cm diameter surfaces. Participants manipulated a metal bucket (12 cm diameter base) with a handle on top (30 cm height). The 300 g bucket was weighted with a 1 kg load, for a total weight of 1.30 kg.

Whole body motions were recorded using XSens Awinda inertial motion capture system (MTw Awinda, XSens Technologies, Enschede, The Netherlands). This system includes 17 3DOF sensors affixed to the body using the included velcro and neoprene straps, headband, shirt, and gloves in the locations specified in Table 2.1 (see also Figure 2.1). Sensor positions and orientations were transmitted wirelessly to the PC and sampled at a rate of 60 Hz. A digital reconstruction of the participant was displayed via MVN Studio v.4.98 (XSens Technologies, Enschede, The Netherlands) and used for motion tracking.

Table 2.1: Locations of the 17 inertial sensors of the MTw Awinda system used for motion tracking

Sensor	**Location**
Head	Posterior skull over the occipital bone
Shoulder (x2)	Over the scapular ridge, right and left
Sternum	Anterior chest over the sternum
Upper Arm (x2)	Lateral aspect, midway between the shoulder and elbow, right and left
Forearm (x2)	Posterior aspect of the forearm proximal to the wrist, right and left
Hand (x2)	Posterior surface of hand, right and left
Pelvis	Over the sacrum
Upper Leg (x2)	Lateral surface of the thigh, midway between the hip and the knee, right and left
Lower Leg (x2)	Medial surface of the tibia, distal to the knee, right and left
Foot (x2)	Superior, lateral surface of foot, over the 5th metatarsal, left and right

Figure 2.1: Photo of the MTw Awinda system used for collection of postural data. Note the inertial sensors that are shown in orange. Image from xsens.com.

2.3.3 – Experimental Procedures and Protocol

This protocol is an adaptation of that used by Rosenbaum et al. (2011), with the task configurations of Rosenbaum (2012). Participants began each trial with their feet on the start position, facing away from the experimental set-up. Upon hearing the “go” command, participants were instructed to turn around (180º), view the environment, and complete the task by proceeding in the most “natural” or “comfortable” manner. Their task was to retrieve the load (bucket) from the table and place it on one of the two target locations (stools), by following the path along either the right or left side of the table. Participants had to choose between completing the task via the rightward path or the leftward path. Once a path was chosen, they were asked to stay along that path until the task was completed, and not cross over to the opposite target stool.

At the beginning of each trial, the load could appear in one of three possible locations: on the left, middle, or right side of the table located at 0.09 m, 0.375 m, and 0.66 m from the table’s left edge, respectively, aligned along the midpoint of the table’s length. The target stools were placed at varying distances, ranging from 1-7 m from the table’s far edge, in 1.5 m increments (Figure 2.2).

Each participant had one fixed target that remained at a distance of 4 m from the table’s far edge for the majority of the experiment, and a variable target that was placed 1, 2.5, 4, 5.5, or 7 m from the table’s far edge. Half of the participants completed the experiment with the variable target along the right path, and the other half completed the experiment with the variable target along the left path, as in Rosenbaum et al. (2011). This was done to ensure path choice was not being biased toward either the fixed or variable side, and so that trial conditions of equal functional distance were not repeated.

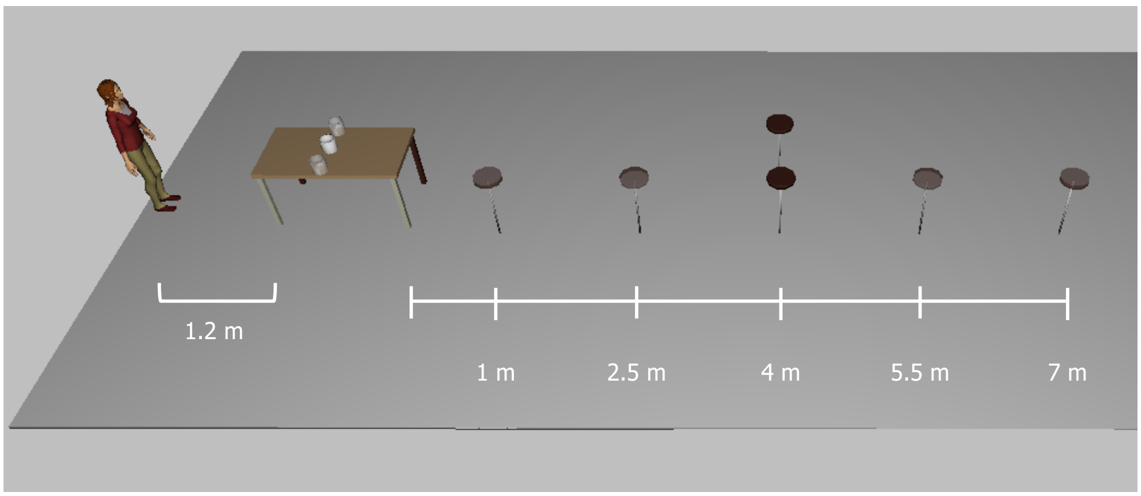


Figure 2.2: Schematic of the experimental set-up. Note that there were 3 possible starting locations of the load (right, middle, left) and the 5 possible variable target locations on the participant's right (at 1, 2.5, 4, 5.5, and 7 m from the table's edge), along with the fixed target location at 4 m on the participant's left. The total distance from the start position to the farthest possible target location is 9.7 m.

Trial target configurations are referred to by the relation between the fixed and variable target locations, allowing for participant data to be pooled regardless of which target was fixed or variable. Differential target distance D_t is defined as the distance of the variable target with respect to the fixed target ($D_t = d_{var} – d_{fix}$). For example, when the variable target is at 1 m, the distance between targets is -3 m (i.e., $D_t = d_{var} – d_{fix} = 1\ m - 4\ m = -3\ m$), therefore D_t of -3 indicates the variable target is 3 m closer to the load than the fixed target. When the variable target is at

4 m, the D_t is 0 m (the targets are equal). In addition, the starting load location is denoted with respect to the variable target side, being near (ipsilateral), central (middle), or far (contralateral) to the path containing the variable target.

There were a total of 30 trials, comprised of three initial load locations (ipsilateral, middle, contralateral), five target configurations (-3 m, -1.5 m, 0 m, 1.5 m, 3 m), and two choice conditions (choice or specified) (Table 2.2). In the first 15 trials, the participant was presented with each task configuration and asked to choose the path that "felt most natural". Path choice for trials 1-15 were recorded by the experimenter. Once all 15 combinations had been completed, trials 16-30 were a replication of trial conditions 1-15 however participants were instructed to complete the task using the opposite path to what they had originally chosen. For example, if on the first presentation of the task, the participant had chosen the right path, they were instructed to proceed along the left path during the second presentation. That is, their path was specified by the experimenter. Trials within the Choice blocks were randomized for each participant.

Table 2.2: Summary of the 30 trial configurations, as a combination of the initial load location, the differential target distance, and the choice condition.

Differential Target Distance D_t	**Choice Condition**					
	Choice			Specified		
	Load Start Location			**Load Start Location**		
	Ipsilateral	Middle	Contralateral	Ipsilateral	Middle	Contralateral
-3	X	X	X	X	X	X
-1.5	X	X	X	X	X	X
0	X	X	X	X	X	X
1.5	X	X	X	X	X	X
3	X	X	X	X	X	X

2.3.4 – Data Analysis

The functional distance (ϕ) of the task was defined by Rosenbaum et al. (2011) as the total distance travelled in metres and incorporates both reaching and walking distances. Rosenbaum et al. (2011) assumed that the internal representation of these distances across different domains would be related linearly, with reaching having an associated scaling factor represented by the equation $\phi = d_{walk} + \beta(d_{reach})$. It was also assumed that the probability of choosing a path would decrease as the difference between the functional distances of the path choices increased, modeled by 1 minus the cumulative density function (cdf) of the standard normal distribution, centered at the point where the difference between functional distances of the two paths is 0 (μ=0, σ=0.5). This would model the probability of choosing one path over the other to a chance value of 0.5 when the functional distances of the paths are equal. The value of β was determined through an iterative process with the goal of finding the value which minimized the sum of squared deviations between the observed choice data and the negative cumulative density function of the normal distribution.

Whole-body motion-capture data were streamed from MVN Studio 4.98 into Jack ergonomic software (Siemens Corp., Ann Arbor, MI), where the motions were aligned to the skeletal segments of a female manikin (digital human model) with the same anthropometric characteristics of the participant. A downward force vector of 12.75 N was applied to the hand used to retrieve the load from the instant the load was lifted. The Task Analysis Toolkit within Jack was used to output a time-history of net joint moments for the shoulder and trunk from the point of the heel strike of the first step forward to the instant when the load was placed on the target, sampled at 30 Hz.

Movement costs at the joints of interest were calculated in two ways for each trial: peak joint load and cumulative joint load. Peak joint load is defined as the maximum absolute net moment in Nm and cumulative joint load is defined as the integral of the absolute net moment-time curve (Nm·s) and was used to provide an account of the total loading incurred at the joint throughout the duration of the trial. These measures were calculated for two areas of interest: 1) the shoulder and 2) the trunk. Shoulder moment is defined as the resultant of the forward-backward rotation moment, abduction-adduction moment, and internal-external rotation moment of the arm that was used to complete the lift. Trunk moment is defined as the resultant of the flexion-extension moment, lateral bending moment, and axial twist moment of the trunk. These measures were chosen to provide insight into how the costs associated with joint demands are prioritized, revealing whether actions are chosen to minimize the absolute load at a given moment in time or if the joint demands over the entire motion are considered during action planning.

2.3.5 – Statistical Analysis

A 2x3x5 repeated measures analysis of variance (ANOVA) was conducted for each of the following dependent variables: 1) peak shoulder moment, 2) cumulative shoulder moment, 3) peak trunk moment, and 4) cumulative trunk moment. The independent variables were choice condition (chosen, specified), load location (ipsilateral, middle, contralateral), and differential target distance (-3, -1.5, 0, 1.5, 3). Since choice was the primary variable of interest to support the hypothesis, simple effects analyses were used to test for significant differences between chosen and specified paths post-hoc, using a Bonferroni correction.

2.4 – RESULTS

2.4.1 – Path Choice

Participant path choice data was pooled so that the probability of choosing the path on the same side as the variable target could be determined. A value of 1 was assigned to trials where the variable path was chosen and 0 was assigned if the fixed path was chosen. Therefore, the probability of proceeding along the path with the variable target P(v) was calculated for each combination of D_t and load location.

Overall, participants were more likely to choose the path with the shorter reach distance (Figure 2.3). The probability of choosing the path with the variable target was 1 when the initial load location was near, for D_t less than or equal to 0. The opposite is true as well, where the probability of choosing the path with the variable target was 0 when the initial load location was far, for D_t greater than or equal to 0. When the initial load location was central, the probability of choosing the path with the variable target was 0.27 when D_t was 0.

To determine if any biases exist in the data with respect to hand preference, these data were also plotted to show the probability of choosing the leftward path, regardless of which path presented the variable target (Figure 2.4). In this figure, the dependent variables are the same, but the y-axis now shows P(Left). One can assume that an absence of hand preference would show these data displayed at a chance value of 0.5. The average probability of choosing the left path when the load began in the ipsilateral location and contralateral location was 0.45 and 0.51, respectively. When the load began in the center location, the probability of choosing the leftward path was 0.61.

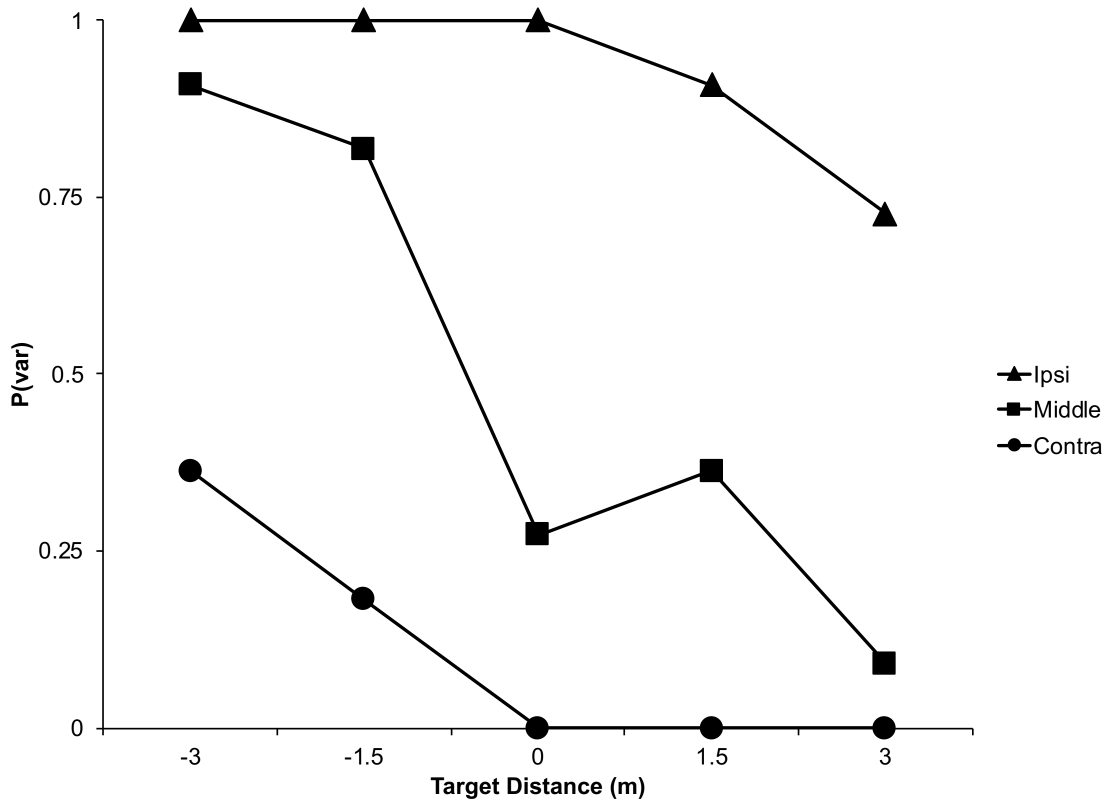


Figure 2.3: Probability of choosing the path along the side of the variable target, given initial load location with respect to the variable target.

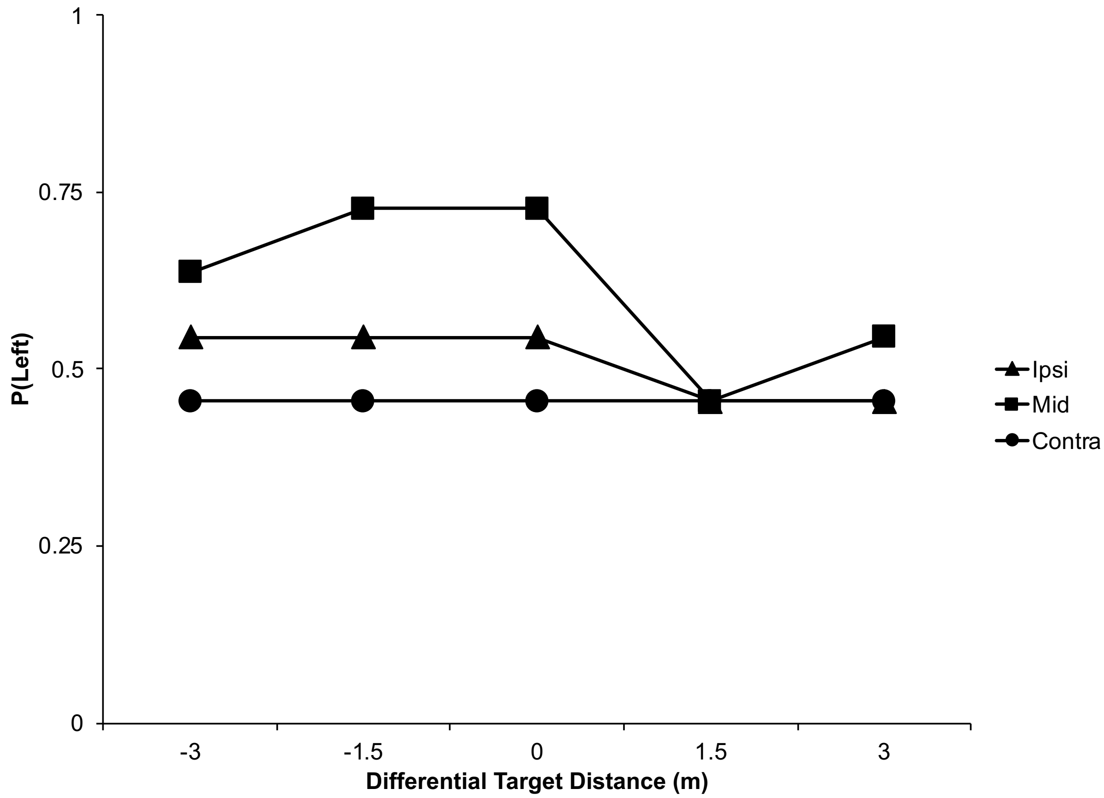


Figure 2.4: Probability of choosing the left path, given the initial load location and differential target distance, with respect to the variable target.

Using the method described in Section 2.3.4, means of the experimental data in each of the conditions were plotted on a single curve by combining the independent variables of reach distance and walking distance into the metric of difference in functional distance ($\Delta\phi$) with respect to the variable target (Figure 2.5). Therefore, each data point is represented by the difference in functional distance between the two alternative path choices (x-axis), and the probability of choosing that path (y-axis), where $\Delta\phi = \phi_{Variable} - \phi_{Fixed}$. For example, a $\Delta\phi$ of 0 represents a D_t of 0 and a middle load start position (i.e., there is no difference between the fixed and variable paths). The β value for these data which minimized the sum of squared deviations was estimated to be 11.158, and this was used to calculate the functional distance of each path. The proportion of explained variance between the experimental data and the theoretical values represented modeled by the 1-cdf of the normal distribution centered at 0 was r^2=0.945. Fisher's z was used to compare the Pearson product-moment correlation of the current study (r = 0.972) to that of Rosenbaum et al. (2011) (r = 0.973) and yielded no significant differences (p>.05).

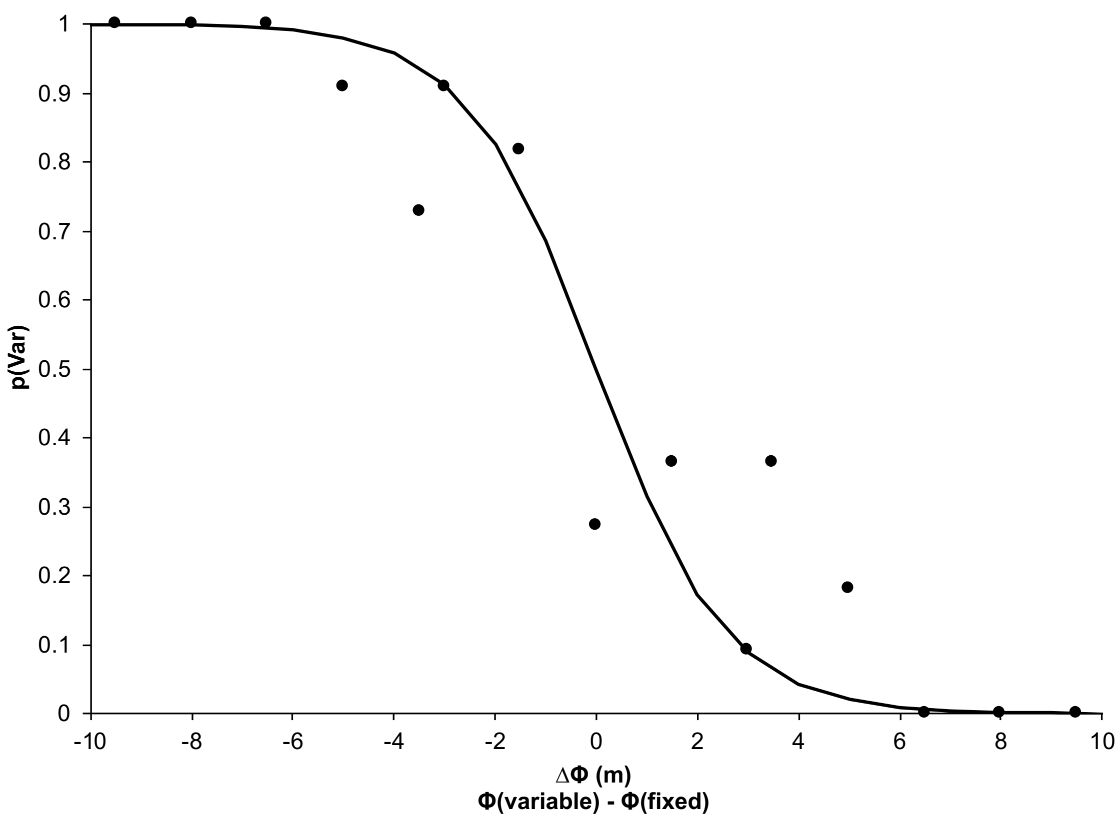


Figure 2.5: Probability of choosing the path with the variable target (p(Var)) plotted as a function of $\Delta\phi$, which represents the difference in functional distances between the fixed and variable paths. Functional distance (ϕ) is the total distance of walking and reaching in metres, defined by the formula $\phi = d_{walk} + 11.16\ (d_{reach})$. Mean probabilities of each of the 15 task combinations are included.

2.4.2 – Biomechanical Analyses

ANOVA were performed for the following independent variables as described in Section 2.3.5. Main effects and interactions were deemed significant if 1) the p-value < .05 and 2) the η^2 accounted for at least 1% of the total variance (adapted from Keppel and Wickens, 2004). The highest-level significant effects for each dependent variable will be reported in the following sections, however p-values and effect sizes of all effects can be found in Appendix E.

2.4.2.1 – Peak Shoulder Moment

There was a significant interaction between choice and load location for peak resultant shoulder moment $F(2,20) = 18.6$, $p < .0001$, $\eta_p^2 = .652$ (Figure 2.6). This effect was significant at the ipsilateral and Contralateral load start positions, with an average shoulder moment increase of 25.1% when the path was specified for participants as compared to when their path was self-chosen. There was no significant difference between peak shoulder moment of the chosen or specified paths when the load began in the middle of the table.

2.4.2.2 – Cumulative Shoulder Moment

There was a significant interaction between choice, load location, and D_t on cumulative shoulder moment $F(2.36, 33.6) = 7.78$, $p < .0001$, $\eta_p^2 = .467$ (Figure 2.7). The Greenhouse-Geiser estimate of the departure from sphericity was $\varepsilon = .659$ and was used to correct the degrees of freedom ($\chi^2(35) = 55.8$, $p = .03$). There are significant differences between the cumulative shoulder load in the chosen versus specified paths when the load was located ipsilaterally to the path with the variable target for all D_t less than or equal to 1.5. This effect is also significant at the contralateral load start location for all D_t greater than or equal to -1.5. There are no significant differences between the cumulative shoulder moments of chosen versus specified paths when the load began in the middle of the table.

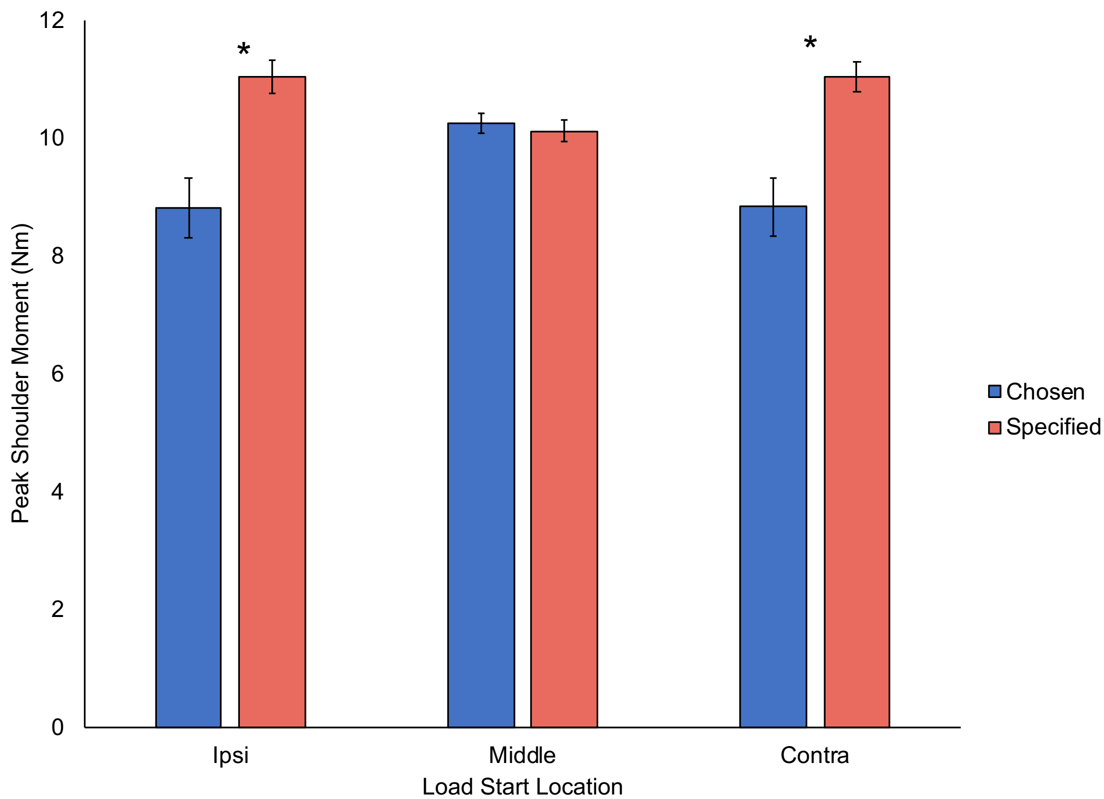


Figure 2.6: Interaction of choice and load location for peak shoulder moment. Means and standard errors are shown (n=55). Significant differences between chosen and specified paths are indicated by an asterisk.

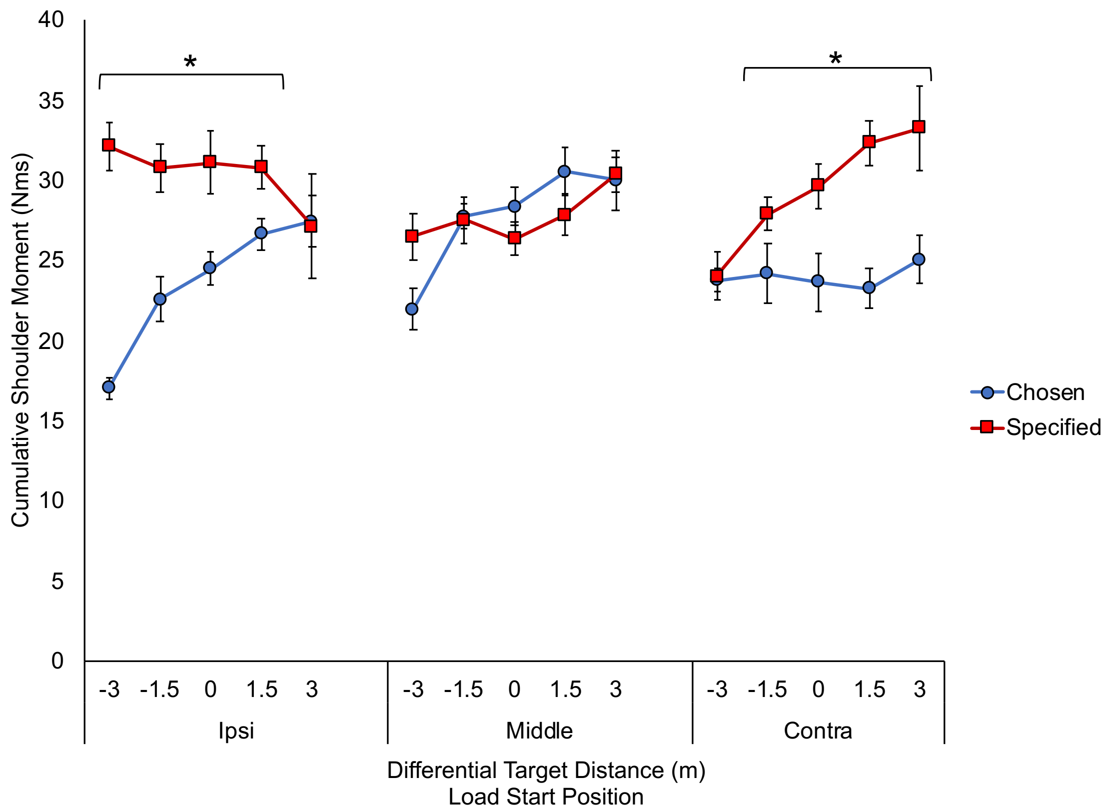


Figure 2.7: Interaction of choice, differential target distance, and load location on the cumulative shoulder moment. Means and standard errors are shown (n=11). Significant differences between chosen and specified paths are indicated by an asterisk.

2.4.2.3 – Peak Trunk Moment

There is a significant interaction effect between choice, load location, and D_t for peak trunk moment $F(8, 80)$ =2.60, p = .014, η_p^2 = .206 (Figure 2.8). There are significant differences between the peak trunk load in the chosen versus specified paths when the load was located ipsilateral to the path with the variable target for all D_t less than or equal to 1.5. This effect is also significant at the contralateral load start location for all D_t greater than or equal to -1.5. There are no significant differences between the peak trunk moments of chosen versus specified paths when the load began in the middle of the table.

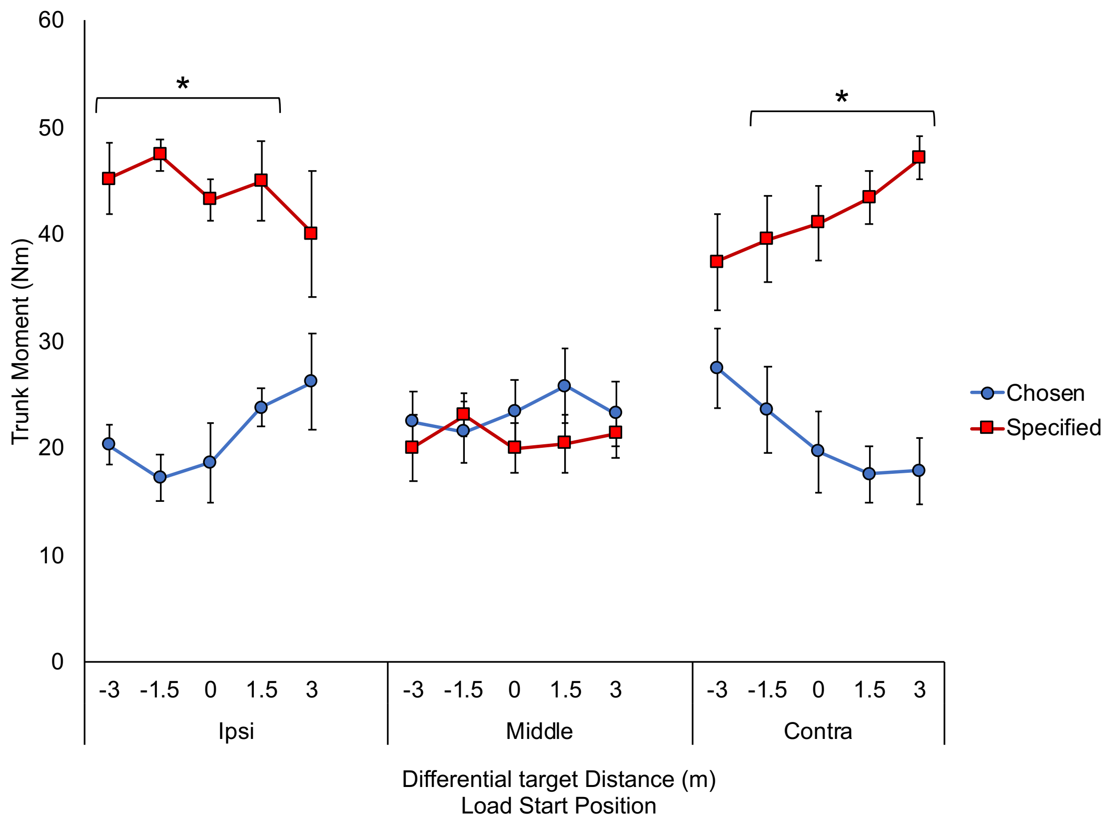


Figure 2.8: Interaction effect between choice, differential target distance, and load location on the peak trunk moment. Means and standard errors are shown (n=11). Significant differences between chosen and specified paths are indicated by an asterisk.

2.4.2.4 – Cumulative Trunk Moment

There was a significant interaction effect between choice, load location, and D_t for cumulative trunk moment $F(2.68, 26.8) = 7.18$, $p < .0001$, $\eta_p^2 = .418$ (Figure 2.9). The Greenhouse-Geiser estimate of the departure from sphericity was ε =

.335 and was used to correct the degrees of freedom ($\chi^2(35) = 63.1$, $p = .006$). There are significant differences between the cumulative trunk load in the chosen versus specified paths when the load was located ipsilaterally to the path with the variable target, for all D_t less than or equal to 1.5. This effect is also significant at the contralateral load start location for all D_t greater than or equal to 0. There is only a significant difference between the cumulative trunk moments of the chosen versus specified paths at $D_t = 1.5$, when the load began in the middle of the table.

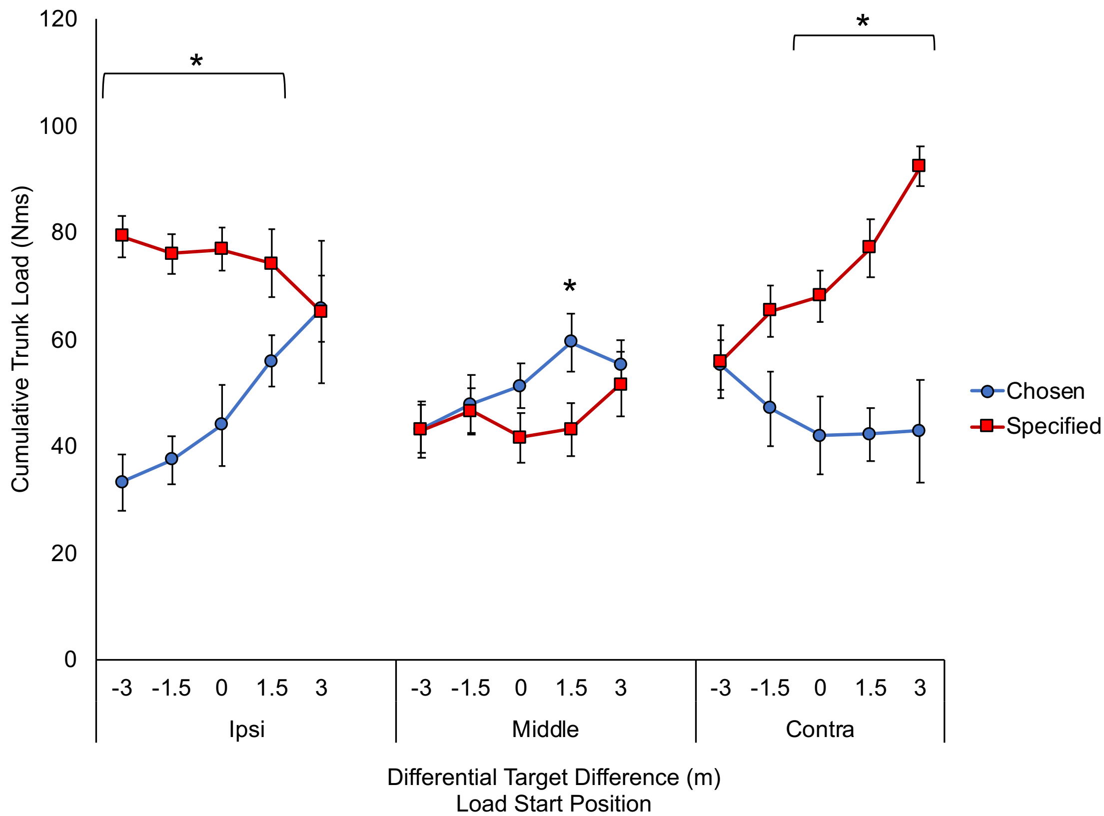


Figure 2.9: Interaction effect between choice, differential target distance, and load location on the cumulative trunk moment. Means and standard errors are shown (n=11). Significant differences between chosen and specified paths are indicated by an asterisk.

2.5 – DISCUSSION

Consistent with the findings of Rosenbaum et al. (2011) and Rosenbaum (2008, 2012), participants chose the path that would primarily minimize reach distance. These observations are further supported by biomechanical data (i.e., shoulder joint and trunk loading). Task paths that were chosen by the participants resulted in decreased peak and cumulative loading at both the shoulder and trunk.

When presented with the choice between a longer reach or a longer walking distance, participants opted for the longer walk, to preserve a reach distance that was a short as possible. The biomechanical data support this, as a shorter reach would result in a decreased moment arm, and therefore a decreased total moment. When the reach distance was equal if approached from either of the path options, distance was then used as the basis for their choice thereby likely establishing a hierarchy for decision making in relation to future action planning. In these instances, the variable path was more likely to be chosen for D_t less than 0 (i.e., when the target was closer to the load), and the variable path was less likely to be chosen for D_t greater than 0 (i.e., when the target was farther from the load).

Similar to the participants in the Rosenbaum studies, the participants in this experiment exhibited a right-handed bias when the load began in the middle of the table. That is, when the reach distance was equal from either side, participants were more likely to walk around the left side of the table so that the bucket could be retrieved with the right hand, their dominant hand. There was one instance however, where our participants differed (at D_t=1.5 with a middle start location).

For this configuration, participants showed no preference for either hand (p(Left)=0.45) (cf. Rosenbaum et al., 2011; Rosenbaum (2012)).

The shoulder and trunk moment data indicate that participants are choosing paths that minimize loading in the task shoulder and at the muscles of the trunk when there is a differential between reach distances of the path choices. This was demonstrated by a likely desire to minimize both the instantaneous loading of the shoulder and trunk, as well as the loading incurred throughout the duration of the trial. The increased loading at these areas during a long reach is likely what the system is perceiving as an increased cost that would serve as a motivator for choosing the path with the shorter reach distance.

Although important information regarding behavioural decision making is obtained from the behavioural outputs alone, the results of this experiment support the idea that biomechanical factors such as joint loading can mediate these behavioural outputs. Typically, it has been suggested that paths are chosen to maintain comfort during a task. These data provide a quantifiable dimension to this subjective construct of comfort.

CHAPTER 3

CHOOSING BETWEEN ACTION ALTERNATIVES IN A TASK ENVIRONMENT WITH UNCONSTRAINED PATHS

3.1 – Abstract

To navigate our surroundings, the human motor system must make decisions about which path or route will be chosen. For example, a decision may need to be made between a path that has a large reach distance and shorter walking distance, or a path with a shorter reach, but requires more walking. Previous research suggests that we are more likely to choose the path that minimizes reach distance, as reaching is ~11x costlier than walking a given distance (Rosenbaum et al., 2011; Rosenbaum, 2012; Chapter 2). Our previous work provides evidence that biomechanical factors, such as joint loading, can drive cognitive decision making when choosing postures for action (Chapter 2). To the best of our knowledge, previous work in this area presented participants with a two-choice model, allowing only the choice between the right or the left paths. Questions remain as to how biomechanical costs and constraints are incorporated into the planning and execution of a decision-making task with increased degrees of freedom. Sixteen female participants performed 50 trials of a bucket transfer task that varied as a function of load start position (near, middle, far, right, left), and load end position (backward, forward, right, left). Behavioural outcomes suggest

that the starting position of the load is incorporated into the decision-making process, reflected in the participants choice of end position. Our data also provide evidence of bottom-up processes influencing action planning, as reflected in decreased cumulative loading measures at both the shoulder and trunk.

3.2 – INTRODUCTION

Recent investigations of reaching and walking behaviour have shown a preference to choose movement paths that prioritize minimizing the cost of reaching, by choosing the path with a shorter reaching distance, even if that means walking a greater distance with the task load (Chapter 2, Potts et al. 2018; Rosenbaum, 2012; Rosenbaum et al. 2011; Rosenbaum 2008). This is because the motor system regards the perceived cost of reaching to be greater than the cost of walking by a factor of about 11 (Chapter 2, Rosenbaum 2012, Rosenbaum et al. 2011). Chapter 2 of this dissertation reports a biomechanical investigation of reaching and walking behaviours by replicating the bucket transfer task used in Rosenbaum et al. (2011). As the increased cost associated with reaching has been postulated to arise from the increased trunk displacement needed to obtain the load when it is placed farther from the body, the main variables of interest were the loading at the shoulder and trunk represented by the resultant shoulder and trunk moments. In addition to replicating the behavioural outcomes of Rosenbaum et al. 2011 (and Rosenbaum 2013), the experiment reported in Chapter 2 revealed a 25% increase in peak shoulder loading and 65% increase in peak trunk loading during tasks with long reaches when compared with shorter reaches. We conclude from these data that behavioural choices were made specifically to minimize the loading at the shoulder and trunk during a decision-making task involving a trade-off between reaching and walking distances.

Currently, the work reported in the literature directly examining a reaching and walking trade-off has only presented participants with a two-choice decision model (i.e., right or left path). This is commonly referred to in decision making studies as a two-alternative forced choice design (2AFC). With the exception of Rosenbaum (2008), the experiments also involved a high degree of constraint wherein participants could only follow unidirectional walking paths along a single movement axis (i.e., a straight, forward path). Additionally, once a path was chosen, participants were required to remain along that path to complete the bucket transfer to the corresponding target destination. Although this type of imposed constraint allows for rigorous (and needed) experimental control, choosing one of only two movement strategies is not necessarily ecologically valid when compared to how reaching and walking movements are coordinated in the performance of activities of daily living.

The experiment reported here aims to extend the current research investigating decision making in a reaching and walking task by introducing a four-alternative forced choice task paradigm. Since it has been established that movement path decisions are influenced more heavily by the reach distances, with reaching imposing a greater cost to the system than walking, this experiment is designed so that the four path choices are of equal distance from the location of load retrieval. Further, this task extends beyond the unidirectional movement sequences tested previously by placing the load centrally with alternative target destinations mapped along the perimeter of the task environment, with some paths requiring either 90º or 180º changes in direction. Changes in direction have been shown to increase the metabolic cost of walking, relative to straight line walking, with a 11.1% increase and 41% increase in energy expenditure for 90º turns and 180º turns, respectively, at an average walking speed (5 km/h) (McNarry et al., 2017). Thus, this task arrangement will impose increased walking costs specific to target placement, independent of walking distance.

Therefore, the purpose of this experiment is to extend the findings of Chapter 2 by increasing the environmental degrees of freedom that can be used to complete the bucket transfer task. The current experiment presents participants with a four-alternative choice paradigm and allows for free movement within the experimental environment. There are two subcomponents of this experiment: the decision-making trials and the target-specified trials. The decision-making trials will serve to probe how participants make choices between action alternatives of equal walking distance in a 360º task environment. All current reaching and walking experiments using the bucket transfer task have placed the target destinations in a forward fashion at the end of the paths. That is, decision making occurred given the constraint of a single, global primary movement axis. This experiment allows path choices to be made to forward, backward, rightward, and leftward targets, which is novel to this line of inquiry. The specified trials will record all task path combinations, so that biomechanical features of all possible movement plans can be analyzed, allowing joint loading to be compared against the preferred or chosen movement paths.

Under these conditions, it is hypothesized that the emergent behaviours in decision-making trials will be chosen to result in the lowest total cost to the system, indicated by reduced biomechanical loading at the shoulder and trunk for each given start location, by choosing strategies that minimize the reach distance during load retrieval. This would reflect backward planning from the movement goal, indicative of bottom-up decision factors driving action planning processes, as was shown in Chapter 2. Additionally, it is hypothesized that path choices will reflect the goal of minimizing the reach distance upon load retrieval.

3.3 – METHOD

3.3.1 – Participants

Sixteen university-aged females (24.75 ± 2.97 years) were recruited from the McMaster University population to participate in this study. All participants were right hand dominant, with a laterality index of 86.88 ± 12.48, as measured by the Edinburgh Handedness Inventory (Oldfield, 1971). All participants were free of any neurological or musculoskeletal disorders and/or symptoms for the 12 months prior to study involvement. Seven of the participants in this study also participated in the experiment outlined in Chapter 2, with 6 months elapsed between the two protocols. Prior to testing, participants were informed of the purpose, methods, and procedures involved in the data collection and provided written informed consent (Appendix C). All portions of this study were approved by, and conducted in accordance with, the McMaster University Research Ethics Board (Appendix A).

3.3.2 – Instrumentation and Data Acquisition

The experimental environment consisted of a 0.75 x 0.75 x 0.76 m table, as well as four bar stools that were 0.63 m in height, with 32 cm diameter surfaces. A metal bucket (12 cm diameter base) with a handle on top (30 cm height) was placed atop the table prior to each trial, with the handle aligned in a sagittal orientation. The 300 g bucket was weighted with a 1 kg bag of lead shot, for a total weight of 1.30 kg, consistent with the load used in Chapter 2. Motion capture data for this experiment were collected using the XSens Awinda system, as described in Chapter 2.

3.3.3 – Experimental Procedures and Protocol

As in Chapter 2, participants started each trial facing away from the experimental set-up, with their feet on the start position which was indicated by a black line of tape on the floor. Once given the “go” command from the experimenter, participants turned 180º to view the environment, before proceeding in manner that they deemed most “natural” or “comfortable” to complete the task of carrying the load to one of the four target stools. The top surfaces of the four target stools were colour-coded using red, green, blue, or yellow electrical tape. Unlike the experimental protocol of Chapter 2, participants were not constrained to a particular linear path. Participants were able to explore the entirety of the space throughout the experimental trials.

The load began in one of five possible locations at the start of each trial: on the middle, right, left, near, or far side of the table (Figure 3.1**)**. The target stools were each placed 4.5 m from the center of the table, in forward (yellow), rightward (red), rearward (blue) and Leftward (green) locations (Figure 3.2). Once the bucket transfer was complete, the load would be reset to the subsequent start location by the experimenter prior to the next trial, while the participant faced away.

Participants completed 50 trials of the bucket transfer task that varied as a function of the load start position (near, center, far, right, left), and target position (backward, forward, rightward, leftward) in four testing blocks (Figure 3.3). Block 1 consisted of 5 trials, where the participant was presented with the load in each of the 5 start positions and asked to choose the target destination that “felt the most natural”. Path choices in trials 1-5 were recorded by the experimenter. Next, block 2 consisted of participants performing 20 trials comprised of one of each of the start location by target end position combinations. In this block of trials, participants were instructed as to which target to carry the load. This was specified by referring to each target by its corresponding colour, as to not explicitly give an instruction of directionality (“bring the bucket to the yellow target”). The third block of 20 trials repeated the procedure from block 2, so that there were a total of two data points per task combination, per participant. The final block consisted of 5 trials, and replicated the protocol of block 1, where participants were able to choose their preferred target destination. A short rest was given between testing blocks. The order of trial presentation within each testing block was randomized for each participant.

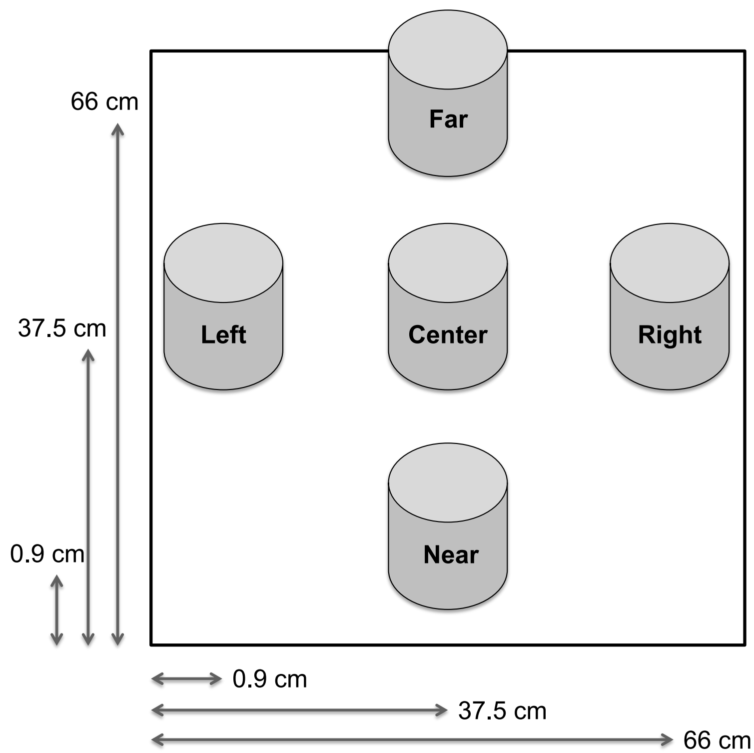


Figure 3.1: Illustration of the 5 possible load (bucket) start locations on the 0.75 x 0.75 m table top. Distances indicate the positioning of the center of the bucket. Note that only one of these loads was present during each experimental trial, in a randomized location. Load magnitude = 1.3 kg.

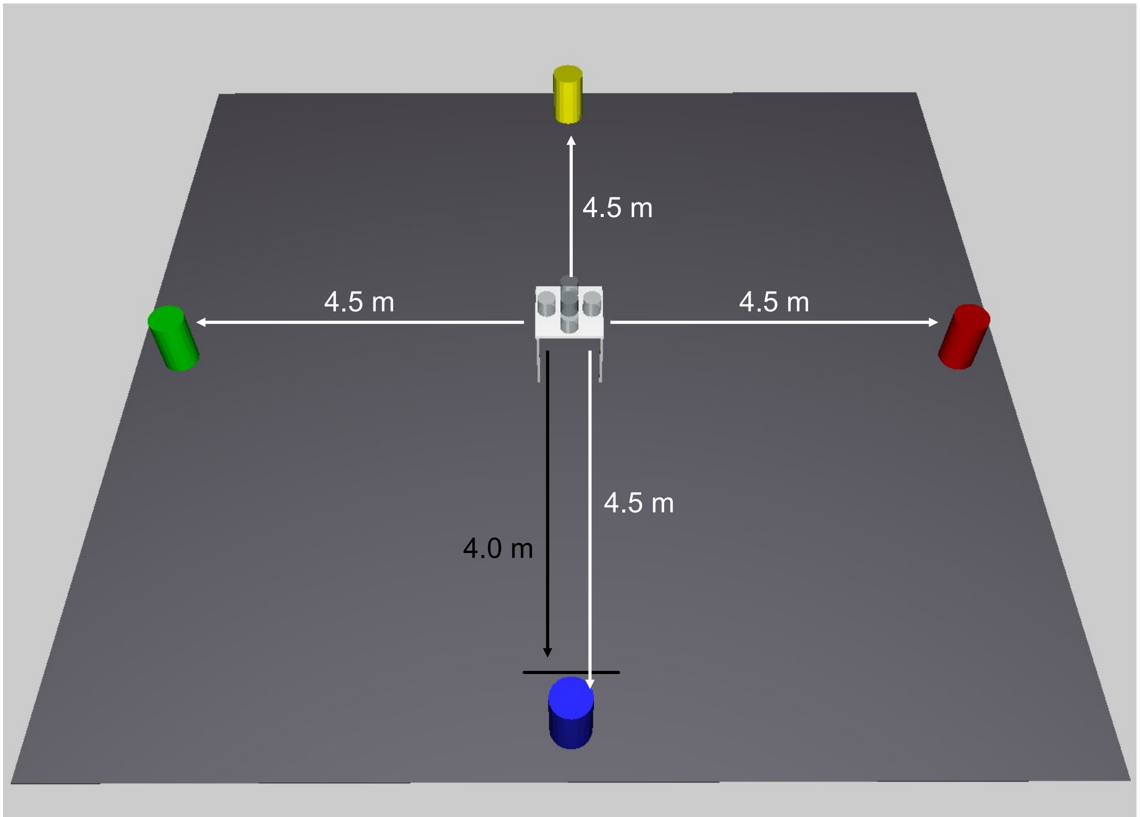


Figure 3.2: Overhead schematic of the experimental environment. Note the 5 possible load starting locations (near, center, far, right, left) and the 4 possible colour-coded target destinations (rearward [blue], forward [yellow], rightward [red], and leftward [green].

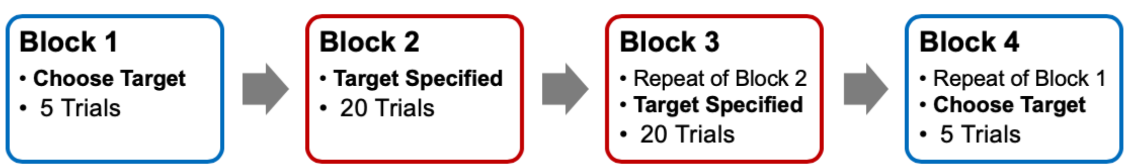


Figure 3.3: Overview of experimental testing procedure. Blocks 1 and 4 contained decision-making trials where participants chose the target destination. In blocks 2 and 3, the target location was specified.

3.3.4 – Data Analysis

Whole-body motion-capture data were streamed from MVN Studio 4.98 into Jack ergonomic software (Version 9.0, Siemens Corp., Ann Arbor, MI), where the motions were aligned to the skeletal segments of a female manikin (digital human model) with the same anthropometric characteristics of the participant. A downward force vector of 12.75 N was applied to the hand used to retrieve the load from the frame before the load was lifted, determined through frame-by-frame visual inspection. The Task Analysis Toolkit within Jack was used to output a time-history of net joint moments from the frame of the first forward heel strike to the frame when the load was placed upon the target stool, sampled at 30 Hz.

Movement costs at the shoulder and trunk were calculated in two ways for each trial using custom LabVIEW software (National Instruments, Austin, TX); peak joint moment and cumulative joint moment. Peak joint moment was defined as the maximum absolute net moment in Nm and cumulative joint moment is be defined as the integral of the absolute net moment-time curve, in Nm·s, and was used to provide an account of the total loading incurred at the joint throughout the duration of the trial. These measures were calculated for two areas of interest: 1) the shoulder and 2) the trunk. Shoulder moment was defined as the resultant of the forward-backward rotation moment, abduction-adduction moment, and internal-external rotation moment of the arm that was used to complete the lift (task arm). Trunk moment was defined as the resultant of the flexion-extension moment, lateral bending moment, and axial twist moment of the trunk.

3.3.5 – Statistical Analysis

A 5x4 repeated measures analysis of variance (ANOVA) was conducted for each of the following dependent variables: 1) peak shoulder moment, 2) cumulative shoulder moment, 3) peak trunk moment, and 4) cumulative trunk moment. The independent variables were load start location (near, center, far, right, left) and target destination (backward, forward, rightward, leftward). All analyses were completed using SPSS Statistics Software Package (Version 21, IBM, Chicago IL). Simple effects analyses were used to test for significant differences between target destinations within each of the load start locations post-hoc, using a Bonferroni correction.

3.4 – RESULTS

3.4.1 – Target Choice

Participant target choices from block 1 and block 4 were pooled to calculate the probability of choosing a particular target given the start location of the load (Figure 3.4). Overall, participants were most likely to choose the backward, forward, rightward, and leftward targets when the load began in the near, center, far, right, or left start locations, respectively. Interestingly, near and center start locations were the only conditions to elicit responses to all four of the target destinations. It should also be noted that choices were made to both the forward and backward target destinations for each of the load start locations.

Looking at blocks 1 and 4 independently gives an indication of how choices changed after participants had experience performing all possible task combinations (Figure 3.5). The forward target was chosen most frequently in block 1, accounting for 33.8% of choices, however the backward target was chosen most frequently in block 4, accounting for 40.0% of choices, across all start locations. It is interesting to note that 2 participants chose only the backward target destination for all choice trials in the experiment.

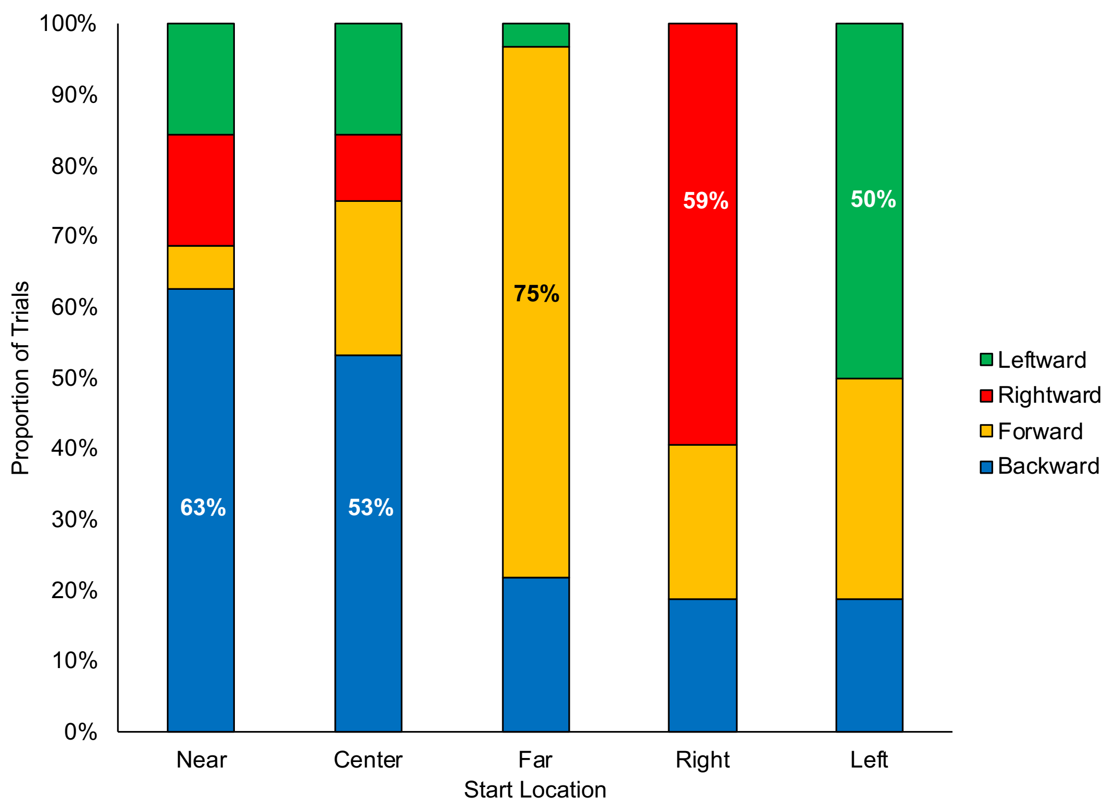


Figure 3.4: Proportion of target destinations chosen for each of the load start locations. The most common choice for each start location is labelled with the percentage of trials in which that target was chosen. Each bar contains 32 trial observations, with a total of 160 observations represented on the graph.

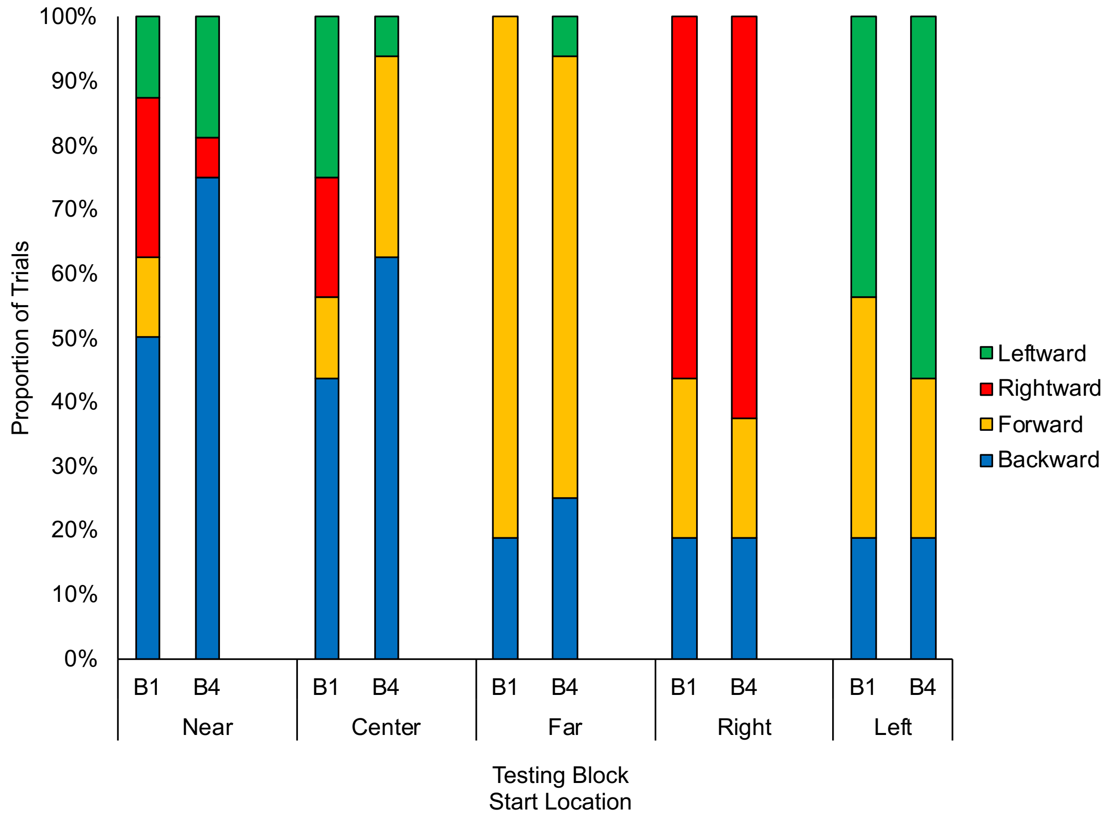


Figure 3.5: Proportion of target destinations chosen for each of the load start locations, decomposed by testing block, block 1 (B1) and block 4 (B4). Each bar is comprised of 16 trial observations, with a total of 160 observations represented on the graph.

3.4.2 – Lift Hand

The hand that was used to grasp the load was observed and plotted for the trials in blocks 2 and 3 (Figure 3.6). There was an overall righthand grasp preference of 64.1%. When the load was transferred to the rightward target, however, left-handed grasps were preferred, with the proportion of right-handed lifts decreasing to 13.1% across these trials. Additionally, left hand grasps were also preferred when the load began in the right location and was transported to the forward target, with the proportion of right handed lifts decreasing to 6.3%.

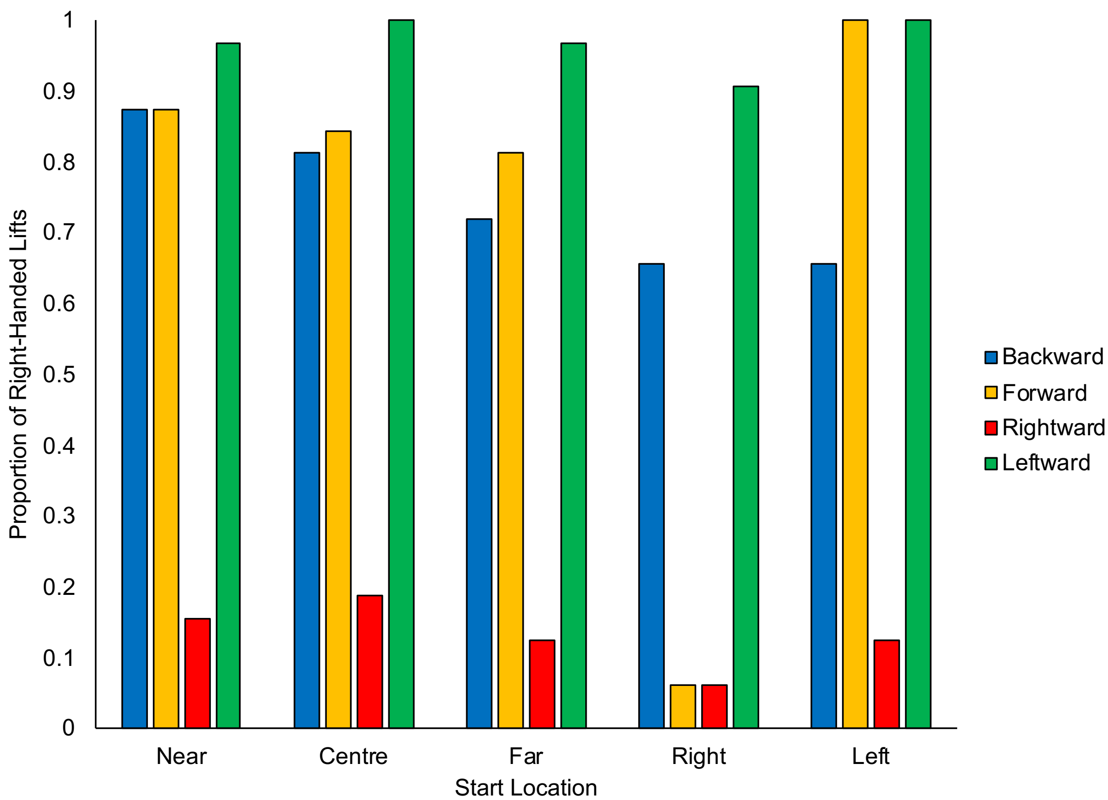


Figure 3.6: Proportion of lifts made with the right hand for each task combination in blocks 2 and 3 (n=32).

3.4.3 – Biomechanical Analyses

ANOVA were performed for the following independent variables as described in Section 3.3.5. Main effects and interactions were deemed significant if 1) the p-value < .05 and 2) the η^2 accounted for at least 1% of the total variance (adapted from Keppel and Wickens, 2004). The highest-level significant effects for each dependent variable will be reported in the following sections, however p-values and effect sizes of all effects can be found in Appendix F.

3.4.3.1 – Peak Shoulder Moment

There was a significant interaction effect between load start location and target destination on peak resultant shoulder moment, $F(5.96, 89.38) = 9.25$, $p<.0001$, $\eta_p^2=.381$ (Figure 3.7). The Greenhouse-Geiser estimate of the departure from sphericity was $\varepsilon=.50$ and was used to correct the degrees of freedom ($\chi^2(77)=106.5$, $p = .036$). This effect was significant at far, left, and right load start locations. When the load began at the far location, there was an 8.6% and 6.2% decrease in peak shoulder moments when the load was carried to forward and rightward locations, respectively, compared to the backward location. When the load began at the right location, transporting the load to the forward target resulted in a 12.5% and 16.0% decrease in peak shoulder moment compared to the backward and leftward targets, respectively. Looking at the left load start location, transporting the load to the forward location yielded a mean peak shoulder moment that was an average of 13.5% lower than transports to the backward, rightward, and leftward target destinations. There were no significant differences between peak shoulder moments measured at each of the target destinations when the load began in the near and center locations.

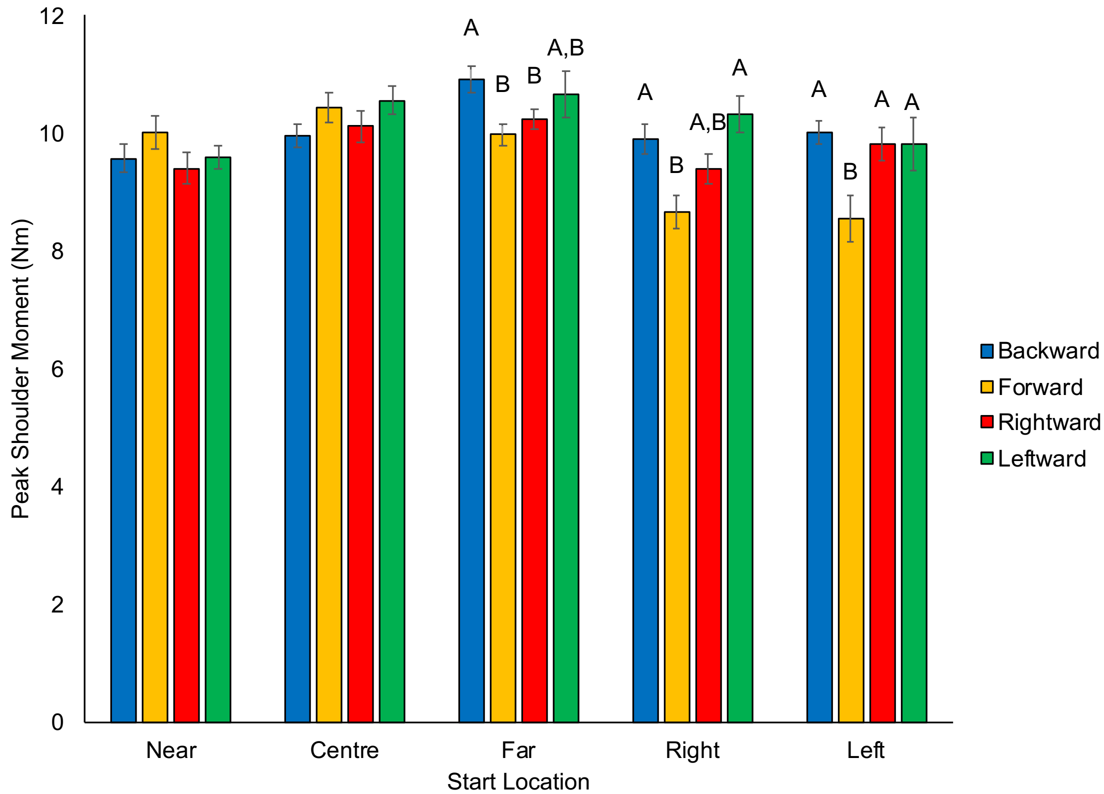


Figure 3.7: Interaction effect between load start location and target destination on the peak shoulder moment. Means and standard errors are shown (n=32). Significant differences between target destinations within a load start location are denoted by letters. Different letters indicate target destinations that are significantly different from each other (e.g. A is significantly different from B, AB is not significantly different from A or B).

3.4.3.2 – Cumulative Shoulder Moment

There was a significant interaction effect between load start location and target destination on peak resultant shoulder moment, $F(12, 180) = 13.72$, $p<.0001$, $\eta_p^2=.48$ (Figure 3.8). This effect was significant at all load start locations except for center, where there were no differences between target destinations. The cumulative shoulder moment increased by 12.7% when the load was carried to the forward target, compared to the other target options, when the load began at the near location. When the load began at the far location, transporting the load to the leftward target resulted in a 10.0% decrease in cumulative shoulder moment compared to the backward target. At the right load start location, transporting the load to the forward or rightward location yielded a cumulative shoulder moment that was on average 14.05% lower than leftward and backward transports. Lastly, carrying the load from the left start location to the yellow target resulted in the lowest cumulative shoulder moment, compared to backward, rightward, and leftward carries.

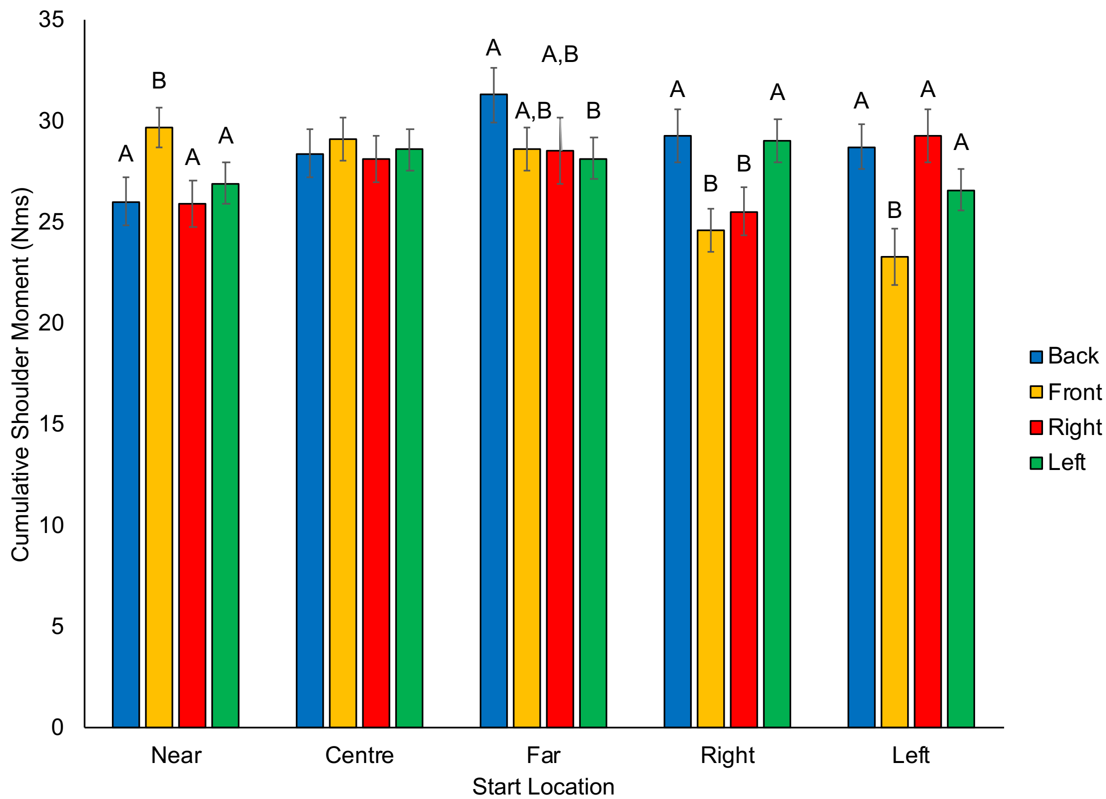


Figure 3.8: Interaction effect between load start location and target destination on the cumulative shoulder moment. Means and standard errors are shown (n=32). Significant differences between target destinations within a load start location are denoted by letters.

3.4.3.3 – Peak Trunk Moment

There was a significant interaction effect between load start location and target destination on peak trunk moment, $F(4.82, 72.30) = 18.37$, $p<.0001$, $\eta_p^2=.551$ (Figure 3.9). The Greenhouse-Geiser estimate of the departure from sphericity was $\varepsilon=.40$ and was used to correct the degrees of freedom ($\chi^2(77) = 115.5$, $p = .09$). Carrying the load from the near start location to the backward target resulted in the highest peak trunk moment, compared to forward, rightward, and leftward targets. When the load began in the center of the table, the peak trunk moment was the lowest for carries to the forward target and increased by an average of 44.5% when the load was carried to the backward, rightward, or leftward targets. Within the far start location, transporting the load to the backward target was 31.9% higher than to either of the lateral targets, which were, in turn, 61.0% higher than transports to the forward target. When the load started on the right, carries to the backward and leftward targets had the highest peak trunk moments, which were 53.8% and 79.6% higher than carries to the rightward and forward targets, respectively. Lastly, load transfers beginning on the left of the table were an average of 40.3% lower for leftward and forward targets than for rightward and backward targets.

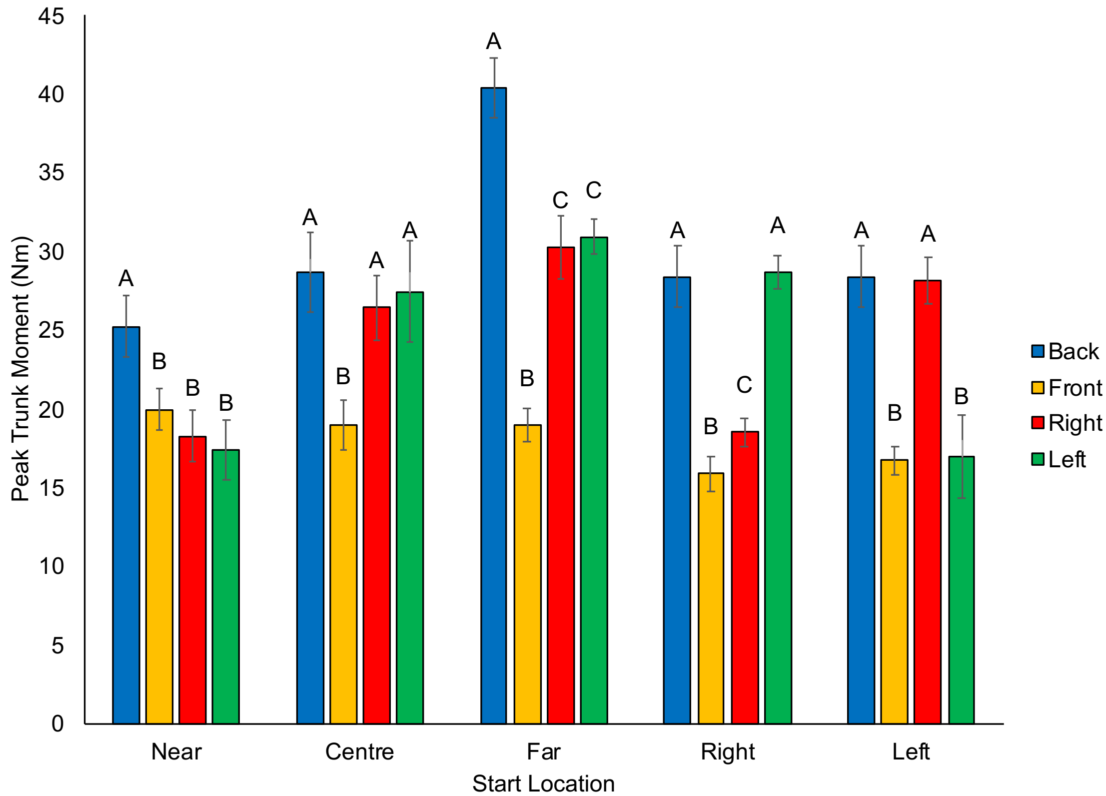


Figure 3.9: Interaction effect between load start location and target destination on the peak trunk moment. Means and standard errors are shown (n=32). Significant differences between target destinations within a load start location are denoted by letters. Different letters indicate target destinations that are significantly different from each other.

3.4.3.4 – Cumulative Trunk Moment

There was a significant interaction effect between load start location and target destination on cumulative trunk moment, $F(12, 180) = 36.33$, $p<.0001$, $\eta_p^2=.707$ (Figure 3.10). Carrying the load from the near start location to either of the lateral targets resulted in cumulative trunk moments that were, on average, 15.4% lower than to the backward or forward targets. When the load began in the center of the table, the peak trunk moment was the lowest for carries to the forward target and increased by an average of 44.5% when carried to the backward, rightward, or leftward targets. Within the far start location, transporting the load to the backward target was 23.8% higher than to either of the lateral targets, which were, in turn, 33.8% higher than transports to the forward target. When the load started on the right, carries to the backward and leftward targets had the highest peak trunk moments, which were an average of 53.5% higher than carries to the rightward and forward targets. Lastly, load transfers beginning on the left of the table were an average of 29.5% lower for leftward and forward targets than for rightward and backward targets.

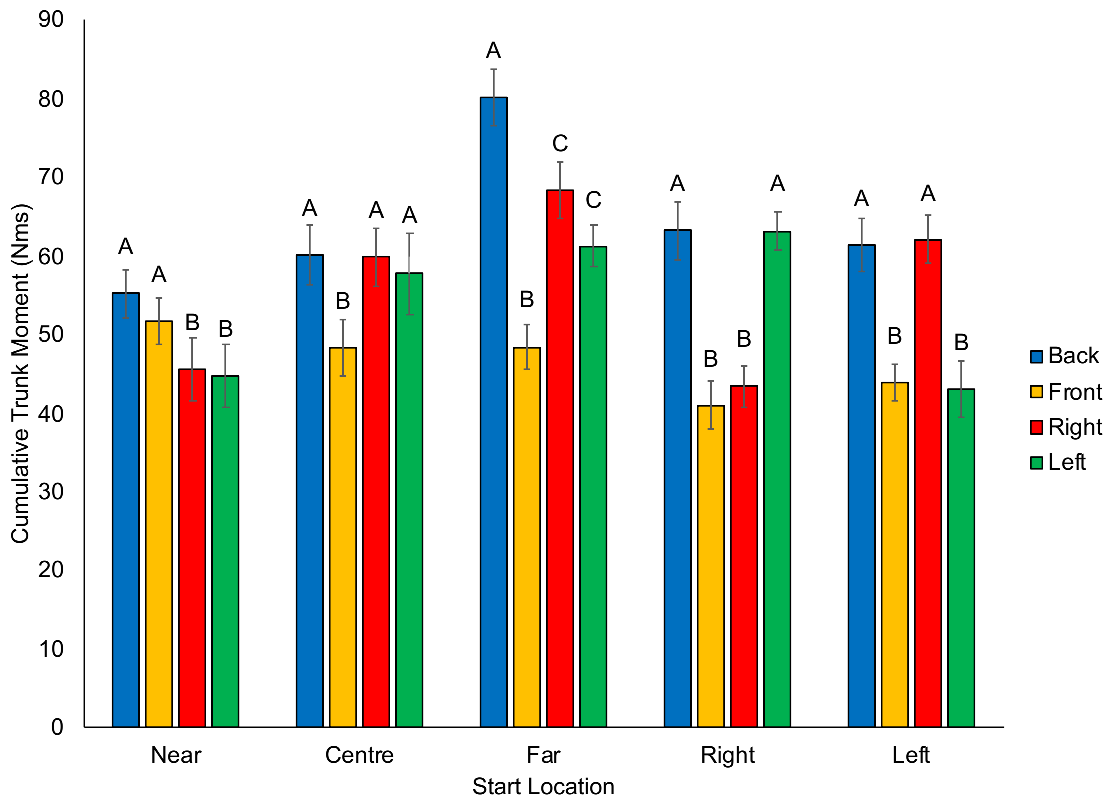


Figure 3.10: Interaction effect between load start location and target destination on the cumulative trunk moment. Means and standard errors are shown (n=32). Significant differences between target destinations within a load start location are denoted by letters.

3.5 – DISCUSSION

This experiment catalogued participant choices in a four-alternative decision-making task within an unconstrained task environment. Although each of the four targets were equidistant from the central table bearing the load, participants were able to choose how the bucket transfer task was completed by deciding which target destination was preferred, and the approach path that would be used to control their reach. Results show a pattern that was primarily spatially coded to the start location of the load (Figure 3.11). In addition, whole-body motion capture was used to compare the loading of the task shoulder and the trunk throughout the entire duration of the trial, between alternative target destinations.

The predominantly chosen target destination for left, right, and far load start locations reflected target choices that minimized the cumulative loading at the trunk, suggesting costs incurred throughout the entire duration of the trial are integrated into the decision-making process, in line with embodied decision theories (Lepora & Pezzulo, 2015; Zgonnikov, Nadim, O'hora, Rañò, & Wong-Lin, 2019). When the load began in the near or center location, however, the rearward target was preferred by participants. This target destination is unique compared to the alternative target choices in that it required a 180º turn to return to the start position. Since a change in direction is less metabolically efficient than walking in a straight line (McNarry, Wilson, Holton, Griffiths, & Mackintosh, 2017), this outcome was contradictory to the hypothesis, as it would lead to an increase cost to the system. Additionally, the biomechanical analyses revealed no mechanical advantage of the backward target choice for either of the joint loading measures at the trunk and shoulder.

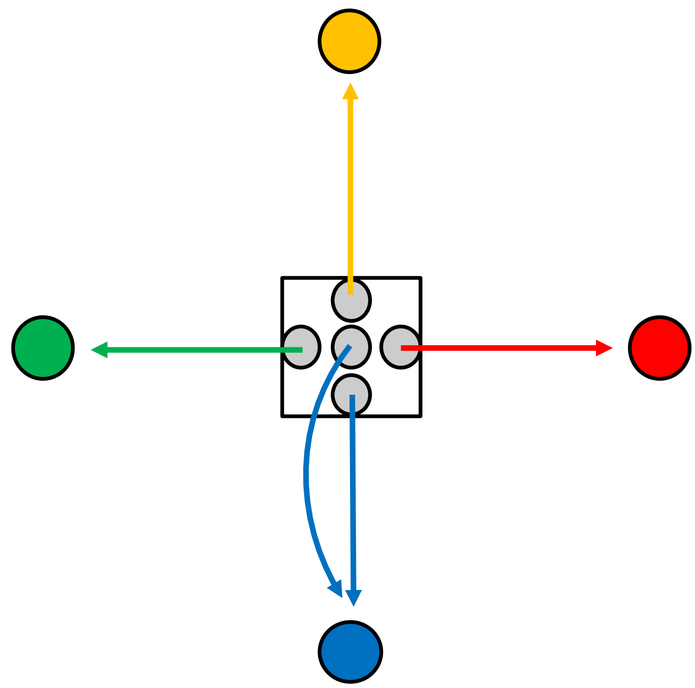


Figure 3.11: Depiction of the most common target choices for each of the load start locations in the decision-making trials (blocks 1 and 4).

Despite movements to the backward target exhibiting cost measures that were greater than, or no different from, the alternative target choices, it was the most commonly selected target for both the near and center load start locations. One possible explanation could be that the walking pattern required to transport the load to the backward target afforded an advantage in the aiming and grasping motion of the arm compared to alternative targets, since a deceleration phase is required before the 180º turn, allowing a slower or more controlled approach. Additionally, at the near load location, approaching the load head-on allowed for the shortest reach distance when compared to the other target destinations. When transporting the near load to the forward or lateral targets, the walking path would deviate to either the left or right side of the table, thereby increasing the length of the reach needed to retrieve the load. The priority to preserve the minimum reach distance supports the results of Chapter 2 and is in line with reaching and walking literature that suggests the cost of reaching is more than 10x greater than the cost of reaching (Potts, Callahan-Flintoft, and Rosenbaum 2018; Rosenbaum 2008; Rosenbaum, Brach, and Semenov 2011; Rosenbaum 2012).

It is interesting to note that many individual behavioural strategies emerged in the decision-making trials. The majority of participants (10/16) displayed an exploratory decision strategy, incorporating all four of the alternative target designations into their movement path selections. Two participants chose three of the destinations only, with one participant avoiding the backward target and one participant avoiding the forward target altogether. There were two participants who excluded the lateral targets from their decision strategy, with 80% of their movement decisions to the same target (one mainly backward and one mainly forward), and the remaining 20% made to the opposite target. Finally, there were two participants who chose to only utilize the backward target.

After their participation in the experiment was completed, these two participants were informally asked why only the backward target was chosen, and both responded similarly, stating that it was chosen so that they did not have to walk back to the home position to reset for the following trial. While returning to the home position was not an explicit component of the task, these participants displayed hierarchical planning of the movement goal at the order of the individual task, and of the experiment as a whole. By returning to the home position while concurrently performing the task goal, these participants chose to expend the added cost of reaching, to conserve the energy that would have been expended walking between trials. Compared to the hypothetical scenario of these participants choosing the forward target in each of the decision-making trials, their backward-only choices halved the total walking distance during blocks 1 and 4. Therefore the difference in walking distance between a backward target only strategy, and choosing an alternate target before returning to the home position could be up to a 9.5 m differential in walking distance per trial. We know from earlier work that the cost of reaching 1 m is approximately 11.0x the cost of walking 1 m, making this differential distance approach the zone of equal walking and reaching costs (i.e., the point of subjective equality) (Rosenbaum et al., 2011; Rosenbaum, 2012; Chapter 2). The largest path differential tested in the reaching and walking literature has been 3.66 m (Potts et al., 2018), so it would be pertinent for future work to explore the reaching and walking trade-off with walking path differential target distances that equal and/or exceed the theoretical cost of reaching.

CHAPTER 4

THE EFFECT OF LOAD MAGNITUDE ON PATH CHOICE IN A DECISION-MAKING TASK

4.1 – Abstract

The human motor system is constantly faced with decisions about how to choose a path when navigating our environment. When deciding between paths that vary in reach distance and walking distance, research shows that the path which minimizes reach distance is more likely to be chosen, as reaching is 11x more costly than walking (Rosenbaum et al., 2011; Rosenbaum, 2012; Chapter 2). There is also evidence that biomechanical factors, such as joint loading, can drive cognitive decision making when choosing postures for action in both a two-choice and four-choice model (Chapter 2, Chapter 3). The purpose of this chapter is to further extend the findings of Chapters 2 and 3 of this thesis by investigating how the perceived costs of *multiple* task variables are prioritized and integrated into action planning. Sixteen participants performed 80 trials of a bucket transfer task that varied as a function of load start position, load magnitude, and end position. These data provide evidence that functional constraints influence action planning, as participants prioritized decreased reach distance over bearing an increased load, reflected in decreased joint loading in chosen versus unchosen paths.

4.2 – INTRODUCTION

Chapter 3 investigated the differing functional demands associated with behavioural decisions in an environment with an increased degrees of freedom, using a four-alternative forced choice decision task. Results provide further support to the notion that biomechanical costs directly influence action planning in a decision task, as choices reflected an interaction between individual structural constraints and the constraints imposed by the task environment. Now, the cost of the action plan must be considered in addition to the cost of the chosen load used to achieve the task goal. Thus far in this dissertation, participants have made decisions about *how* the task will be completed, however in the present chapter, they will also be making decisions about *what* task to complete.

In a task environment with multiple degrees of freedom, the preference for reaching or walking may be affected by factors such as reach distance and load weight. In a lifting task, participants showed a preference to reach a farther distance for a 6 kg load compared to a 16 kg load (Faber et al., 2007). This modified behavioural strategy resulted in reductions in the net trunk moment, despite the associated increase in reaching distance (Faber et al., 2007). Conversely, Konemann et al. (2015) saw no effect of object weight on reaching distance when participants performed a pick and place task, citing that the loads used in their study (0.2 kg and 3 kg) may have been too small to elicit a behavioural change. In this repetitive task, however, participants displayed a preference to reach, rather than walk, to retrieve items from a bin (Konemann et al., 2015). Thus, altering task variables such as load or frequency may lead to a redistribution of the costs associated with reaching and walking behaviors.

When presented with a task that could be completed using one of two load options placed at various distances along the length of the path, a behavioural phenomenon termed pre-crastination has been observed (Rosenbaum et al., 2014). Here, pre-crastination, as opposed to procrastination, is used to describe the tendency to complete the first encountered subgoal of a task as soon as possible, despite any added movement expense that this choice may include. In the context of their 2014 experiment, and similar to the bucket transfer task used in Rosenbaum et al. (2011) and in Chapter 2, when given the choice between two loads at varying distances along a path (i.e., a path with a shorter approach distance that would require carrying the load for a longer duration, or a path that requires walking a greater approach distance, yet a shorter carrying duration), participants chose the seemingly irrational action of retrieving the nearer load and incurring the increased cost of carrying it over a greater distance (Rosenbaum et al., 2014). In this experiment, action outcomes were constrained to a walking forward along single path, with the option to only choose the load to the left or the right of the walking path.

The proposed mechanism for this effect is the need to reduce the load on working memory imposed by task goal as soon as possible (Rosenbaum et al., 2014). As hypothesized by these researchers, perceiving the near object elicits an automatic, ecological-based response by activating the objects affordance to be acted upon, thus enabling the resources of working memory to be allocated elsewhere (Fournier, Stubblefield, Dyre, & Rosenbaum, 2018). An increase in pre-crastination behaviour during a dual-task paradigm with increased cognitive load and an increase in reaction time for tasks that were pre-crastinated (compared to those that were procrastinated) provide support to the pre-crastination-affordance theory (Blinch & DeWinne, 2019; Fournier et al., 2019). Interestingly, however, when a load was chosen between two with differing magnitudes (empty bucket vs. 3.2 kg load), the pre-crastination effect diminished, suggesting that load selection is sensitive to the total incurred cost (Rosenbaum et al., 2014). As such, participants preferred to retrieve the lighter load in 70% of trials, regardless of whether it had the shortest approach distance.

The loads in Rosenbaum et al. (2014) were placed 9 inches from the midline of the participant on either side, at hip height, allowing them to be retrieved with minimal involvement of the torso and while maintaining a relatively neutral shoulder posture. Decision making revealed hierarchical planning that prioritized either: a) a minimized approach distance when loads were of equal magnitudes, or b) minimizing the total load lifted when magnitudes differed. The motor system was not sensitive to the added cost of retrieving the earliest load, however it was sensitive to the increased cost of the heavier load. A series of experiments using similar methodology investigated how the costs of reaching and walking are integrated into action planning, and provide evidence that minimizing the total reach distance of the task is prioritized, as reaching is more costly than walking

(Rosenbaum, 2008; Rosenbaum, Brach, & Semenov, 2011; Rosenbaum, 2012; Chapter 2). How then, are these costs organized in the context of each other?

The original pre-crastination experiments did not vary the reach distances of the loads, nor the interaction between reach distance and load magnitude interaction. Thus, the motivation for the present investigation was to address the gap in the literature that exists at the intersection of the literature investigating the trade-off between the costs of reaching and walking, and the literature investigating the costs associated with choosing between loads of differing magnitudes. At the time of experimental conception and data collection, of the work presented in this chapter, there were no published experiments which directly addressed this gap. Recently, however, Potts et al. (2018) investigated the effect of load magnitude and reach distance on movement path selection, extending Rosenbaum et al. (2014). The pre-crastination effect superseded the cost of increased reach distance when the cost imparted by the load was small (i.e., an unloaded bucket); however, as the magnitude of the load increased (thus increasing the costs associated with reaching), the need to minimize reach distance was prioritized (Potts et al., 2018). Questions remain, however, regarding how these added costs are interpreted by the motor system, and how much more costly the unchosen movement path and alternative task load are compared to the path that was chosen.

The purpose of this study, therefore, is to further investigate how the cost of external task variables are prioritized and integrated into action planning. This investigation extends the result of Chapter 3 by incorporating the choice between a light-weight and heavy-weight within an unconstrained task environment with four decision alternatives. In this experiment, action planning must now incorporate decisions regarding the functional costs imposed by the chosen load in addition to the reaching and walking costs associated with the target destination choice. A choice must be made if decreased reaching costs, for example, can offset the cost of the heavier load, or if it is more preferable to carry a lighter load over a larger functional distance.

It was hypothesized that the chosen behaviour will be driven by the goal of minimizing cumulative loading throughout the carrying portion of the task, specifically in the trunk and shoulders. This goal criterion would be logical, since the optimal strategy would be to carry the lighter load for a shorter duration. Rosenbaum et al. (2014) observed that participants chose the lighter load 70% of the time. The biomechanical measures collected in this experiment may provide insight into the underlying factors that led to the heavy load being chosen in 30% of trials.

4.3 – METHOD

4.3.1 – Participants

Sixteen right-handed, university-aged females participated in this study (24.75 ± 2.97 years; laterality index = 86.88 ± 12.48). The participants in this experiment were the same 16 participants from the experiment in Chapter 3, seven of whom also participated in the experiment of Chapter 2. The collection of Chapter 3 and Chapter 4 occurred concurrently and was counterbalanced such that 8 participants completed the experiment in Chapter 3 first and the remaining 8 participants completed the present experiment first, before participating in the other. There was a minimum of 48 hours between the two experimental testing sessions. As in Chapters 2 and 3, participants were free of any musculoskeletal disorders or symptoms for the 12 months prior to study involvement. All portions of this study were approved by, and conducted in accordance with, the McMaster University Research Ethics Board (Appendix A). Before participating the experiment, participants provided informed consent (Appendix D).

4.3.2 – Instrumentation and Data Acquisition

The experimental set-up was very similar to that used in Chapter 3, with a 0.75 x 0.75 x 0.76 m table used to present the task loads, as well as four bar stools that were used as target destinations (Figure 3.2). The unique feature of this experiment was that there were now two metal buckets with the same dimensions as the ones used in the experiments of Chapter 2 and Chapter 3. One bucket was weighted with a 1 kg bag of lead shot, for a total weight of 1.3 kg, and the second bucket was weighted with a 3.6 kg bag of lead shot, for a total load of 3.9 kg. The 1.3 kg load is consistent with the load that was used in the experiments of Chapters 2 and 3, and the 3.9 kg load was determined through pilot testing and adapted from the 7 lb load used in the literature (Rosenbaum et al., 2014; Potts et al., 2018). This second task load was 3x the magnitude of the original load and was chosen because it was heavy enough that it posed a challenge to the system, but not so heavy that it would be avoided altogether. Additionally, the buckets were colour coded; one of the buckets was silver and the other was black. The loading of the buckets was counterbalanced among participants such that the 1 kg load was in the silver bucket and the 3.6 kg load was in the black bucket for half of the participants, and vice versa for the remaining participants. Whole body motion capture data for this experiment were collected using the XSens MTw Awinda system, as described in Chapter 2 and used in Chapter 3.

4.3.3 – Experimental Procedures and Protocol

As in the previous chapters, trials began with the participants standing on the start position, turned to face away from the experimental environment. After a “go” command was given by the experimenter, participants made a 180º turn to view the environment and then proceed in the most “comfortable” and/or “natural manner to complete the task. The task had the same objective as in the previous experiments: carry the load to one of the four target stools and place the load atop the surface. The colour-coding system was used to differentiate the alternative target destinations, as in Chapter 3. Again, the participants were encouraged to move freely within the experimental space and were not constrained to a predetermined path.

The novel feature of this experiment was that there were now two loads presented at the start of each trial, a light load (1.3 kg) and a heavy load (3.9 kg). Recall that the load was colour-coded by either a black or silver bucket and whether the light load was in the silver bucket or the black bucket was counterbalanced among participants. There were 8 possible variations of the load start orientations that used the same absolute load locations from Chapter 3 (Figure 3.1). There was always one load that was fixed in the center of the table, and the load of opposite magnitude was located either in the near, far, left, or right location (Figure 4.1). Therefore, there were 4 load start locations with the heavy load in the center and the light load placed in one of the 4 remaining locations, and 4 load start locations with the light load in the center and the heavy load placed in one of the 4 remaining locations. For the remainder of this chapter the load orientations will be referred to with respect to the load that was placed toward the perimeter of the table (i.e., "heavy-far" indicates that the heavy load was in the far location and the light load was in the center).

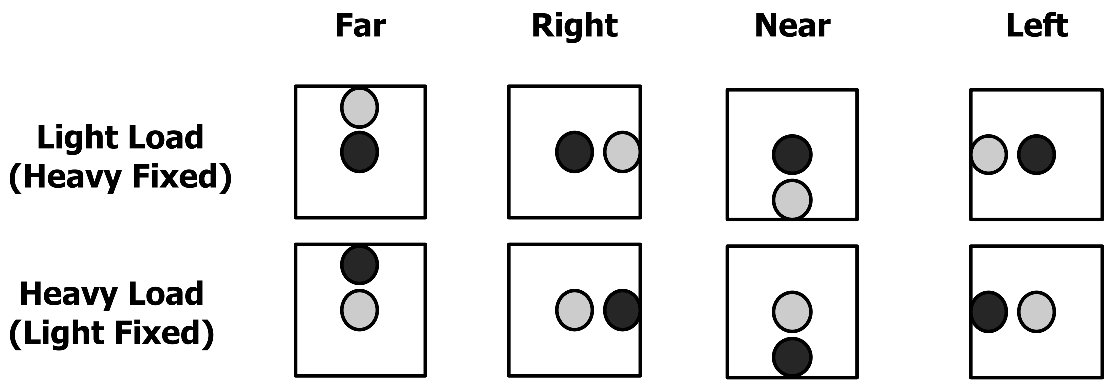


Figure 4.1: Overhead schematic of all 8 load start orientations. The dark grey circles represent the placement of the heavy load and the light grey circles represent the placement of the light load. Absolute load locations follow the same conventions as used in Chapter 3 (Figure 3.1). Note that in each of the orientations there were two loads present, with one load always in the center location, and the load of opposite magnitude placed in either the far, right, near, or left location.

There were a total of 80 trials in which participants completed a bucket transfer task. These trials varied as a function of load configuration (light-near, light-far, light-right, light-left, heavy-near, heavy-far, heavy-right, heavy-left), and target destination (backward, forward, rightward, leftward). Testing occurred in 4 blocks, combining elements of the experimental designs used in both Chapter 2 and Chapter 3 (Figure 4.2). In Block 1, participants were asked to choose one of the two loads from the central table and carry it to the target destination of their choice. There was a trial for each load start orientations, for a total of 8 trials in block 1 where participants determined a) which load they would transport, and b) which of the 4 end positions they deemed most preferable. In block 2, participants were instructed as to which target destination to carry the load to, but they were given the choice of retrieving the light or the heavy load. As in Chapter 3, target destinations were indicated by referring to each target stool by its corresponding colour (red, blue, green, yellow), as to not explicitly give an implicit instruction of directionality. Block 2 consisted of 32 trials; one for each of the load start orientation (n=8) and target destination (n=4) combinations. Block 3 repeated the same trial conditions that were presented in Block 2, but now participants were instructed to retrieve the opposite load as to what was chosen in Block 2. In this way, blocks 2 and 3 mimic the experimental design used in Chapter 2 so that movement characteristics of the chosen and non-chosen load could be compared. Load magnitudes were referred to by the colour of the bucket (silver or black), as to not explicitly bias the perceived weight of the object. Participants were naïve to the fact that they would be asked to perform the opposite of their original choice before block 3. Block 4 consisted of the same 8 dual-choice task trials as presented in Block 1. The order of trial presentation within each testing block was randomized for each participant.

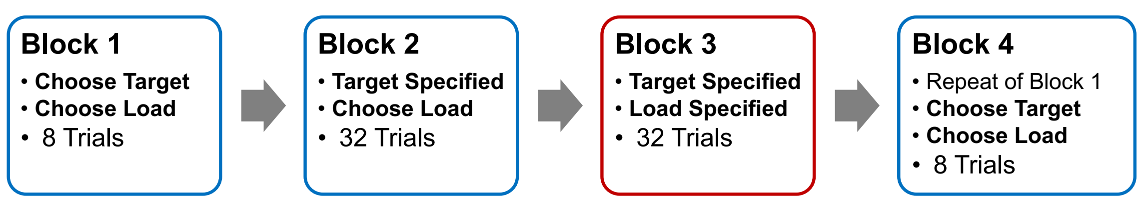


Figure 4.2: Overview of experimental testing procedure. Blue outlines indicate blocks with decision-making trials, and red outlines indicate blocks where the task parameters were specified for the participant. In blocks 1 and 4 participants chose both the load to be carried and the target destination. In block 2, the participant chose the preferred load, but target location was specified by the experimenter. In block 3, both the load and the target destination were specified for the participant, with the load being the opposite to what was chosen in block 2.

4.3.4 – Data Analysis

Data analysis for this experiment followed the same procedures as outlined in section 3.3.4, except that the downward load vector added to the task arm at the instant of the grasp corresponded to the magnitude of the load that was lifted during that trial. A vector of 12.75 N was applied when the light load was grasped and a vector of 38.26 N was applied when the heavy load was grasped.

4.3.5 – Statistical Analysis

A 2x4x2x4 repeated measures analysis of variance (ANOVA) was conducted for each of the following dependent variables: 1) peak shoulder moment, 2) cumulative shoulder moment, 3) peak trunk moment, and 4) cumulative trunk moment. The independent variables were choice condition (chosen, specified), variable load location (near, far, right, left), variable load magnitude (light, heavy), and target destination (backward, forward, rightward, leftward). Since choice was the primary variable of interest to support the hypothesis, simple effects analyses were used to test for significant differences between chosen (block 2) and specified (block 3) trials post-hoc, using a Bonferroni correction factor.

4.4 – RESULTS

4.4.1 – Target Choice

Participant target choices from block 1 and block 4 were pooled to illustrate the probability of choosing a particular target given the start location of the load (Figure

4.3). Participants chose the backward target destination most frequently across all load start orientations, accounting for 36.7% of the total choices. Responses were made to all four target destinations in every start orientation except for light-far, where no responses were made to the leftward target. The backward target was the most commonly chosen destination when the light load was placed centrally, and the heavy load varied. When the heavy load was fixed centrally and the light load varied, the target choice preferences were as follows: backward, forward, rightward, and leftward, for light-near, light-far, light-right, and light-left orientations, respectively.

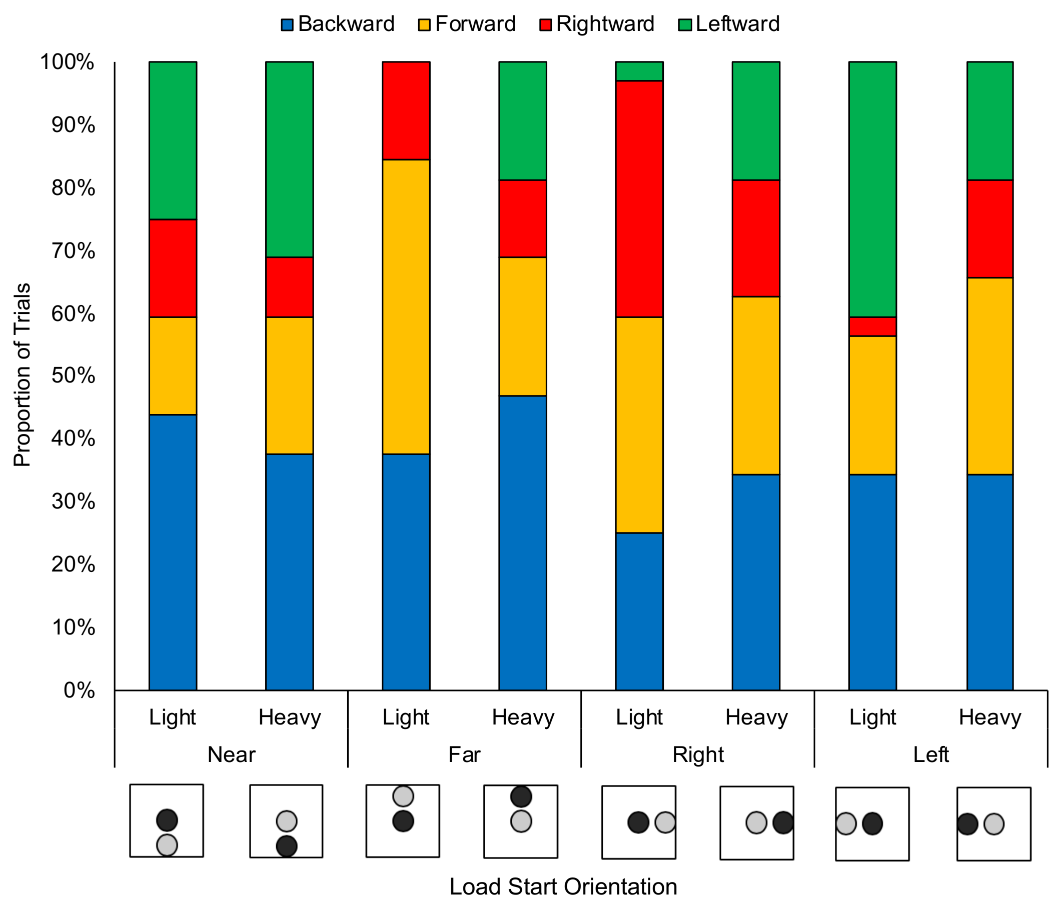


Figure 4.3: Proportion of target destinations chosen for each of the load start orientations in blocks 1 and 4. Different colour bar segments represent the target destination that was chosen. Each bar contains 32 trial observations, with a total of 256 observations represented on the graph.

4.4.2 – Load Choice

Participant load choices in blocks 1 and 4 were pooled to depict the prevalence of choosing the light or the heavy load, given the start orientation of the loads (Figure 4.4). Carrying the light load was preferred in 75.8% of trials, across load orientations. It is important to note that the light load was the predominant choice for all start orientations in the free choice blocks, except for heavy-near where the heavy load was favoured by 63%.

Participant choices in block 2, where the target was specified are indicated in Table 4.1. A one-proportion z-test was used to test whether the predominant load choice in each load orientation x target destination task condition differed from a chance value of 50% and revealed the critical proportion of 75% (z = 2.0, n = 16, p = .05). These data are also represented in a graphic to better illustrate the spatial relationship between load choices, the initial orientation of the loads, and the indicated target destination (Figure 4.5). When transporting to the backward target, the load that began in the center of the table was the most likely to be chosen, regardless of load magnitude. When transporting to the forward target, the light load was chosen for all start orientations except for heavy-left. Transfers to the rightward target favoured the right-most load in right and left arrangements, and the most proximal load in near and far arrangements. Similarly, the left-most or most proximal load was predominantly chosen for transfers to the leftward target.

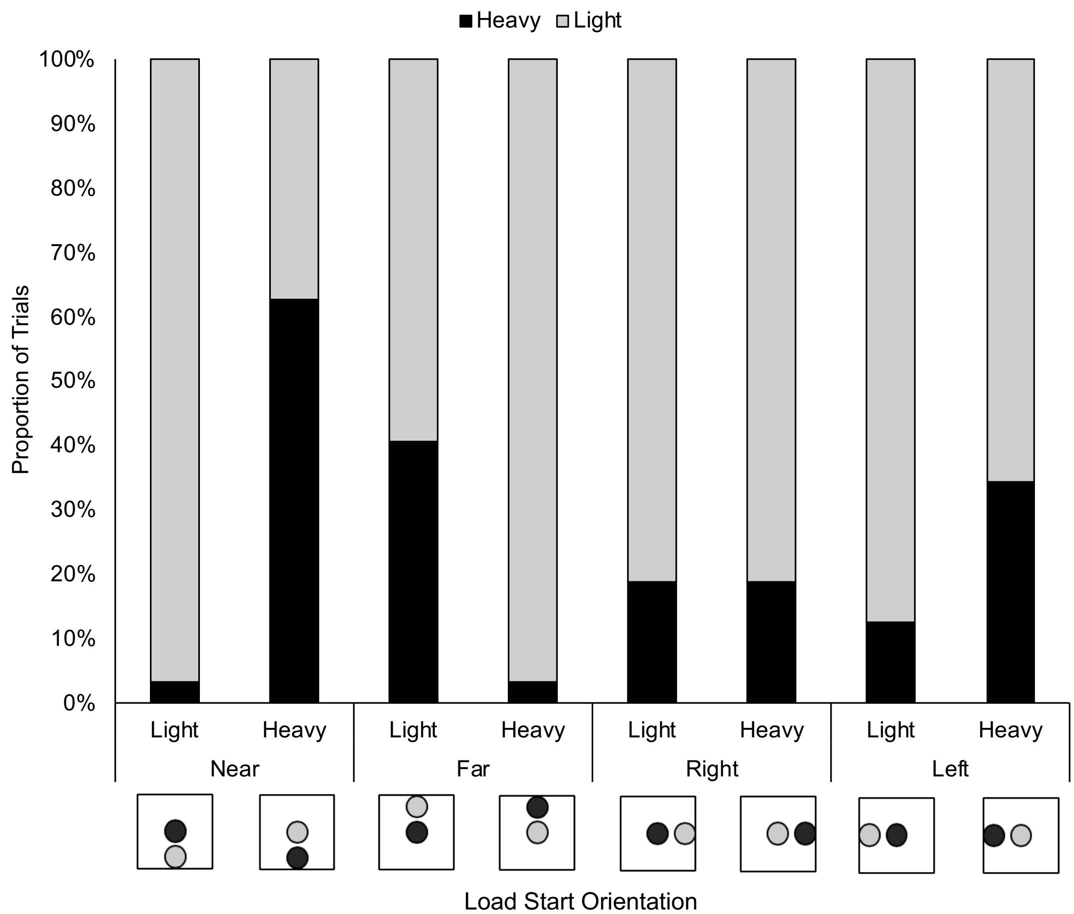


Figure 4.4: Proportion of light versus heavy load magnitudes chosen for each of the load start orientations in blocks 1 and 4. Light grey bar segments represent the light load (1.3 kg) and dark grey bar segments represent the heavy load (3.9 kg). Each bar contains 32 trial observations, with a total of 256 observations represented on the graph.

Table 4.1: Load choice results for trials in block 2, where the target destination was specified, and the load magnitude was chosen. For each combination of load start location, load magnitude, and target destination, the proportion of the predominant load choice is indicated by the percentage, and the shading of the cell indicates whether that proportion refers to the light load (white) or the heavy load (grey). For example, when the loads began in the light-near configuration, 94% of participants chose the light load to transport to the backward target, while 6% (1-.94) chose the heavy load. Each cell represents 16 observations. Significant differences from chance values as tested by a one-sample proportional z-test are denoted by asterisks (**p*<.05, ***p*<.01, ****p*<.001).

Variable Load Location	Variable Load Magnitude	Target Destination			
		Backward	Forward	Rightward	Leftward
Near	Light	94%***	94%***	94%***	94%***
	Heavy	69%	81%*	75%*	56%
Far	Light	69%	88%**	75%*	63%
	Heavy	94%***	81%*	94%***	94%***
Right	Light	75%*	69%	94%***	63%
	Heavy	100%***	94%*	69%	94%***
Left	Light	69%	100%***	63%	94%***
	Heavy	88%**	56%	94%***	69%

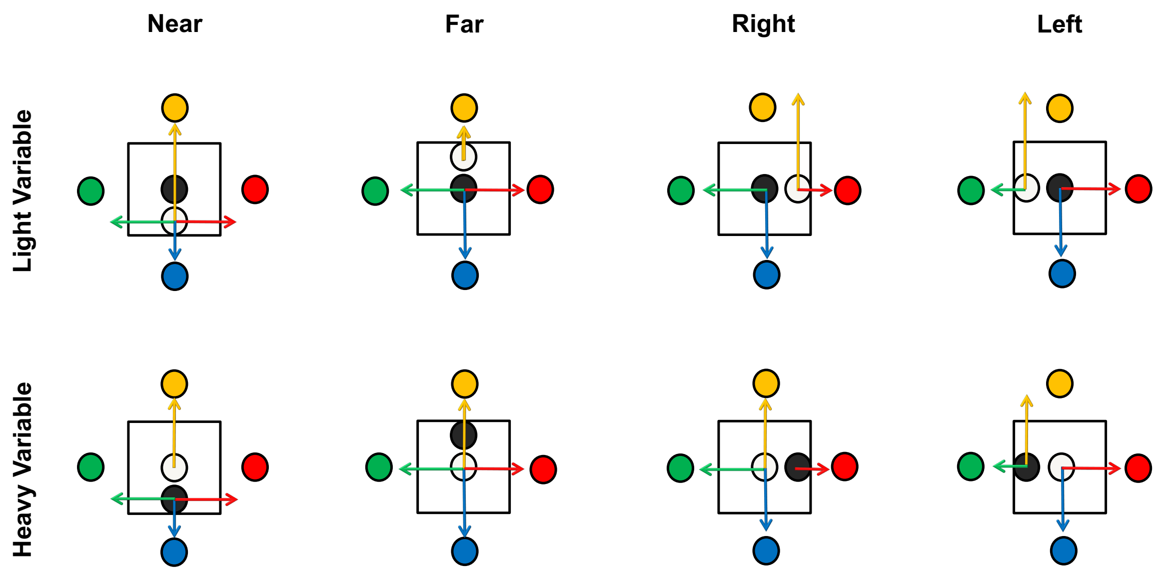


Figure 4.5: Schematic depicting the most commonly chosen load magnitude for each task combination (load orientation x target destination) (graphic representation of Table 4.1). Each system illustrates a birds-eye view of the experimental environment, with blue, yellow, red, and green circles representing the backward, forward, rightward, and leftward targets, respectively, white circles representing the light load location and black circles representing the heavy load location. Coloured arrows indicate the specified target destination, with the arrow originating in the target that was most chosen for that condition.

4.4.3 – Biomechanical Analyses

ANOVAs were performed for the following independent variables as described in Section 3.3.5. Main effects and interactions were deemed significant if: 1) the p-value was less than 0.05 and 2) the η^2 accounted for at least 1% of the total variance (adapted from Keppel and Wickens, 2004). The highest-level significant effects for each dependent variable are reported in the following sections; however, p-values and effect sizes of all effects can be found in Appendix G.

4.4.3.1 – Peak Shoulder Moment

There was a significant four-way interaction between load choice, variable load location, variable load magnitude, and target destination on the peak shoulder moment, $F(2.54, 38.1) = 13.1$, $p < .0001$, $\eta_p^2 = .467$. The Greenhouse-Geiser estimate of the departure from sphericity was $\varepsilon = .282$ and was used to correct the degrees of freedom ($\chi^2(44) = 100.5$, $p < .0001$). The three-way interactions between load choice, variable load location, and target destination are shown separately for variable load magnitudes of light (Figure 4.6 a) and heavy (Figure 4.65 b). Only significant differences between chosen (block 2) and specified (block 3) trials will be noted.

4.4.3.1.1 – Light Load Variable

Light-Near: There was a 47.3% reduction in peak shoulder moment, on average, for load transports to all target destinations when the load was selected by the participant. Light-Far: Carrying the chosen load to the forward target resulted in peak shoulder moments that were 36.3% lower than with the specified load. Light-Right: The peak shoulder moment was decreased by 45.2% and 27.9% when chosen loads were carried to the rightward and backward targets, respectively, compared to when specified loads were carried to the same target destinations. Light-Left: A 56% and 44.3% reduction in peak shoulder moment was measured for chosen load transports to the forward and leftward targets, respectively, compared to specified load transports.

4.4.3.1.2 – Heavy Load Variable

Heavy-Near: Carrying the chosen load to the forward target resulted in peak shoulder moments that were 28.6% lower than with the specified load. Heavy-Far: There was a 42.7% reduction in peak shoulder moment, on average, for load transports to all target destinations when the load was selected by the participant. Heavy-Right: The peak shoulder moment decreased by an average of 40.8% when chosen loads were carried to all target destinations except for the rightward target. Heavy-Left: The peak shoulder moment was decreased by 37.9% and 41.3% when chosen loads were carried to the rightward and backward targets, respectively, compared to when specified loads were carried to the same target destinations. The peak shoulder moment was 36% higher when carrying the load to the leftward target, compared to carrying the specified load to the same target.

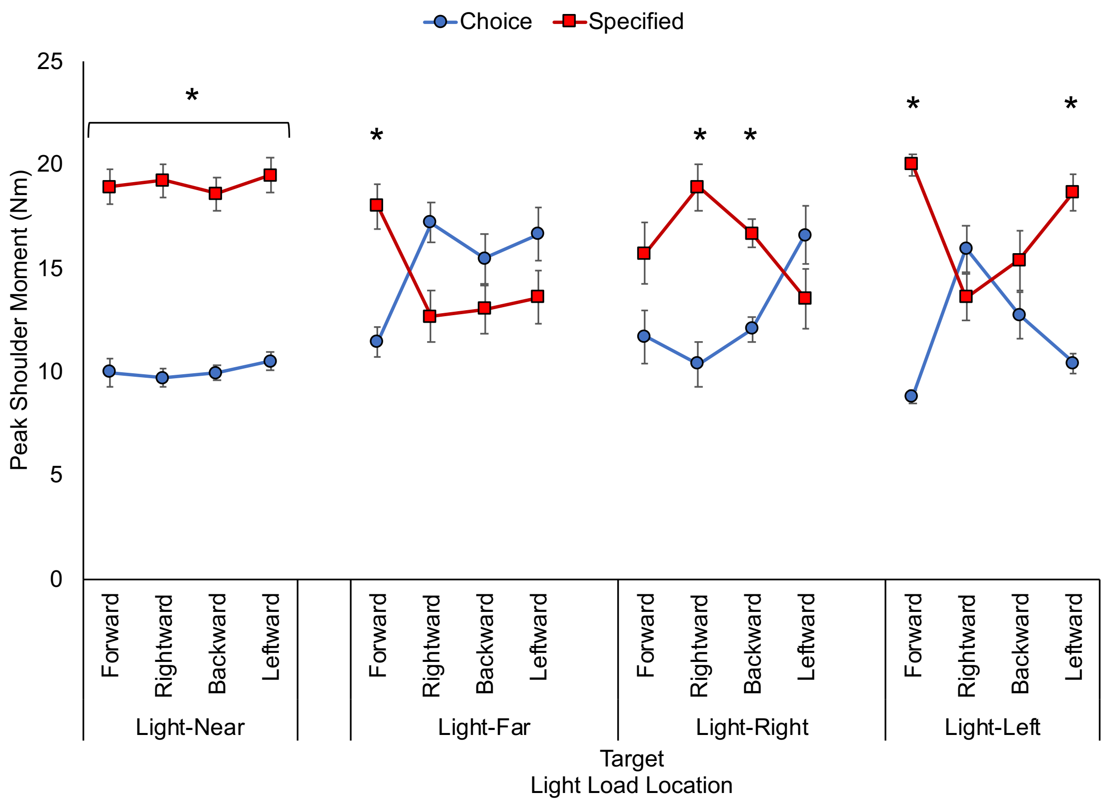


Figure 4.6 a): Interaction effect between choice, load location, and target destination on the peak shoulder moment for the light load magnitude. Mean and standard errors are shown (n = 16). Significant differences between choice conditions are indicated by an asterisk.

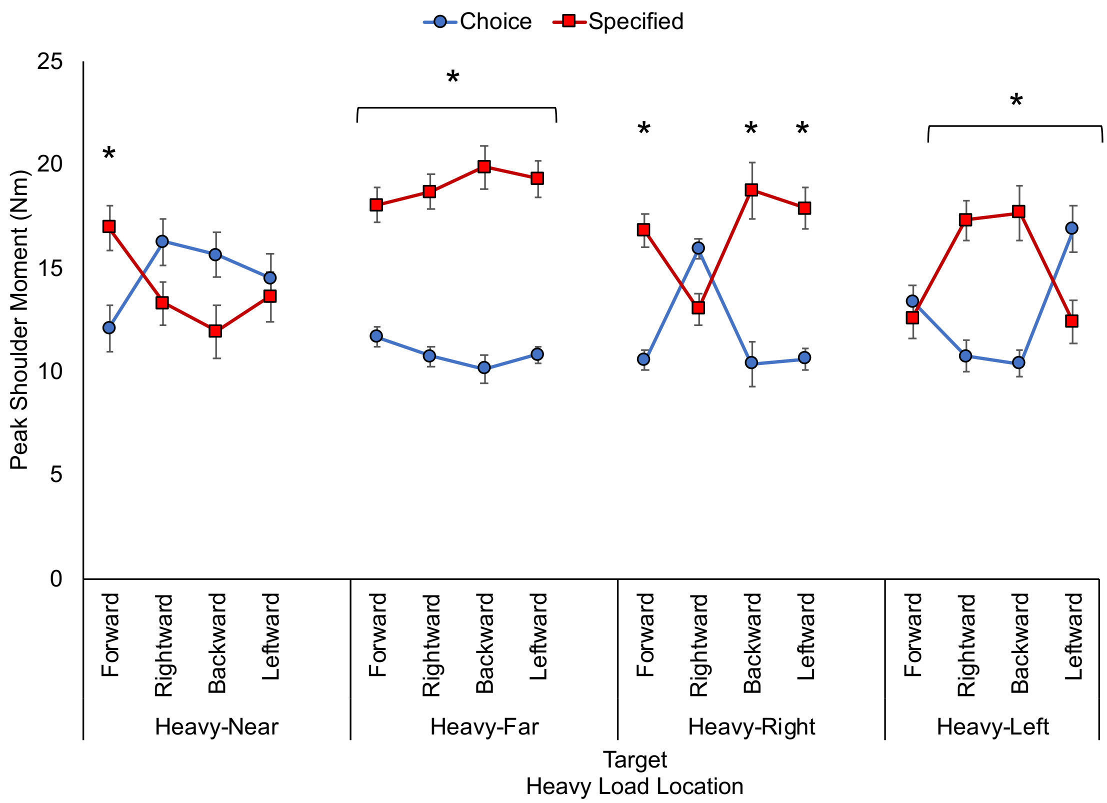


Figure 4.6 b): Interaction effect between choice, load location, and target destination on the peak shoulder moment for the light load magnitude. Mean and standard errors are shown (n = 16). Significant differences between choice conditions are indicated by an asterisk.

4.4.3.2 – Cumulative Shoulder Moment

There was a significant four-way interaction between load choice, variable load location, variable load magnitude, and target destination on the cumulative shoulder moment, $F(2.29, 34.32) = 13.2$, $p < .0001$, $\eta_p^2 = .468$. The Greenhouse-Geiser estimate of the departure from sphericity was $\varepsilon = .254$ and was used to correct the degrees of freedom ($\chi^2(44) = 112.1$, $p < .0001$). The three-way interactions between load choice, variable load location, and target destination are shown separately for variable load magnitudes of light (Figure 4.7 a) and heavy (Figure 4.7 b). Only significant differences between chosen (block 2) and specified (block 3) trials will be noted.

4.4.3.2.1 – Light Load Variable

Light-Near: There was a 19.3% reduction in cumulative shoulder moment, on average, for load transports to all target destinations when the load was selected by the participant. Light-Far: A 37% reduction and 32% increase in cumulative shoulder moment was measured for chosen load transports to the forward and rightward targets, respectively, compared to specified load transports. Light-Right: Carrying the chosen load to the rightward target resulted in peak trunk moments that were 40.6% lower than with the specified load. Light-Left: A 46.3% and 41.2% reduction in cumulative shoulder moment was measured for chosen load transports to the forward and leftward targets, respectively, compared to specified load transports.

4.4.3.2.2 – Heavy Load Variable

Heavy-Near: Carrying the chosen load to the forward target resulted in peak trunk moments that were 37% lower than with the specified load. Heavy-Far: There was a 33.9% reduction in cumulative shoulder moment, on average, for load transports to all target destinations when the load was selected by the participant.

Heavy-Right: The cumulative shoulder moment decreased by an average of 35.2% when chosen loads were carried to all target destinations except for the rightward target. Heavy-Left: The cumulative shoulder moment was decreased by 35.3% and 34% when chosen loads were carried to the rightward and backward targets, respectively, compared to when specified loads were carried to the same target destinations.

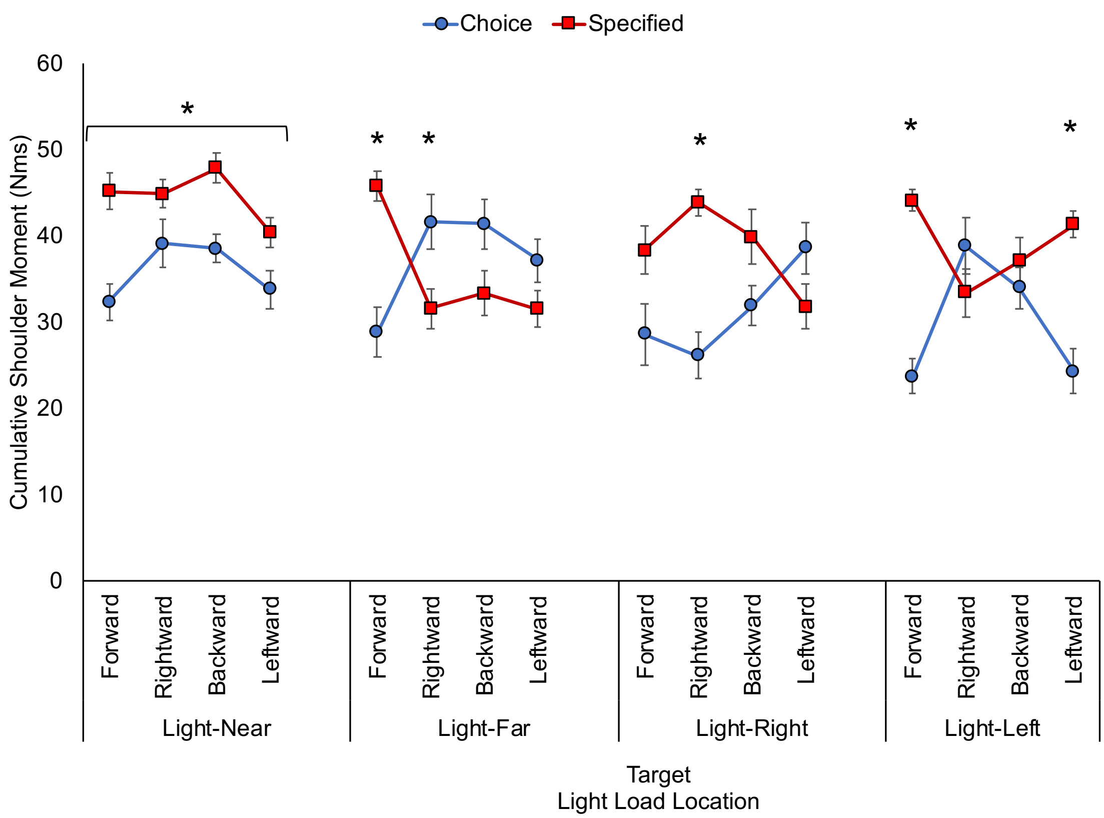


Figure 4.7 a): Interaction effect between choice, load location, and target destination on the cumulative shoulder moment for the light load magnitude. Mean and standard errors are shown (n = 16). Significant differences between choice conditions are indicated by an asterisk.

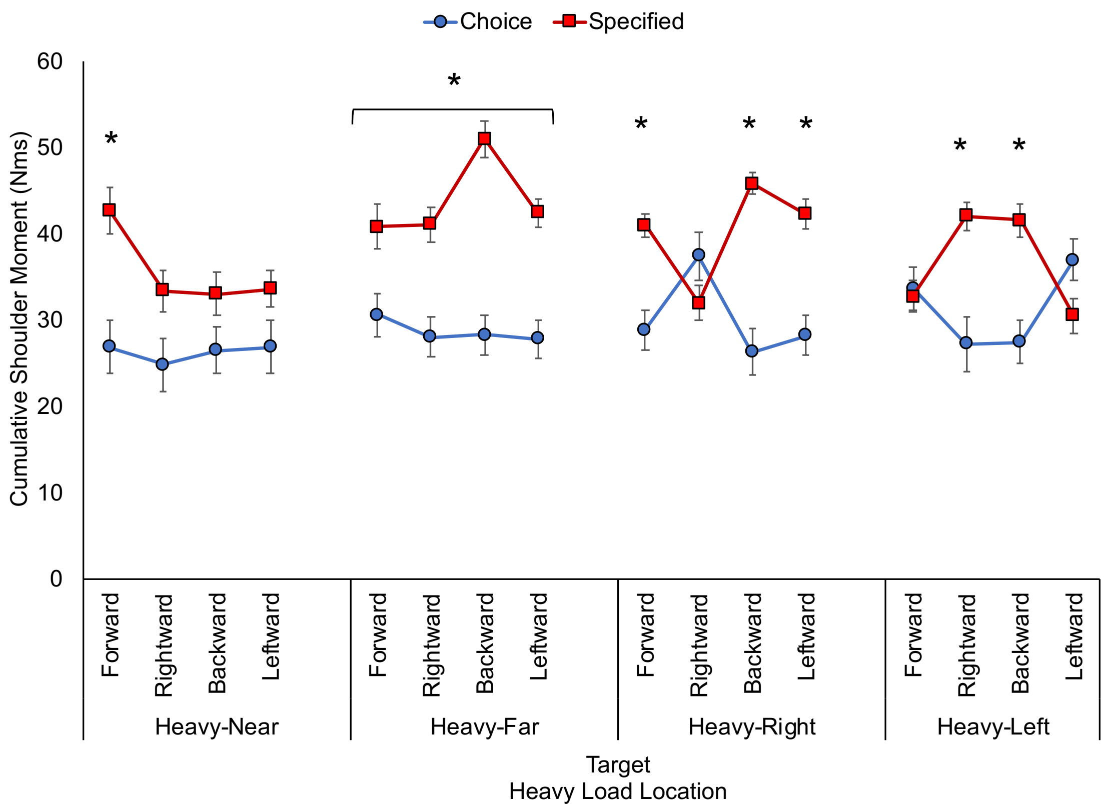


Figure 4.7 b): Interaction effect between choice, load location, and target destination on the cumulative shoulder moment for the heavy load magnitude. Mean and standard errors are shown (n = 16). Significant differences between choice conditions are indicated by an asterisk.

4.4.3.3 – Peak Trunk Moment

There was a significant four-way interaction between load choice, variable load location, variable load magnitude, and target destination on the peak trunk moment, $F(2.75, 41.3) = 10.3$, $p < .0001$, $\eta_p^2 = .408$. The Greenhouse-Geiser estimate of the departure from sphericity was $\varepsilon = .306$ and was used to correct the degrees of freedom ($\chi^2 = 92.8$, $p < .0001$). The three-way interactions between load choice, variable load location, and target destination are shown separately for variable load magnitudes of light (Figure 4.8 a) and heavy (Figure 4.8 b). Only significant differences between chosen (block 2) and specified (block 3) trials will be noted.

4.4.3.3.1 – Light Load Variable

Light-Near: There was a 42.5% reduction in peak trunk moment, on average, for load transports to all target destinations when the load was selected by the participant. Light-Far: Carrying the chosen load to the forward target resulted in peak trunk moments that were 27.3% lower than with the specified load. Light-Right: The peak trunk moment was decreased by 48% when the chosen load was carried to the rightward target, compared to when the specified load was carried to the rightward target. Light-Left: A 42.2% and 48.6% reduction in peak trunk moment was measured for chosen load transports to the forward and leftward targets, respectively, compared to specified load transports.

4.4.3.3.2 – Heavy Load Variable

Heavy-Near: There were no significant differences between load choice at this location. Heavy-Far: There was a 28.7% reduction in peak trunk moment, on average, for load transports to all target destinations when the load was selected by the participant. Heavy-Right: The peak trunk moment decreased by an average of 33.6% when chosen loads were carried to all target destinations except for the rightward target. Heavy-Left: The peak trunk moment was decreased by 34.9% and 24.4% when chosen loads were carried to the rightward and backward targets, respectively, compared to when specified loads were carried to the same target destinations.

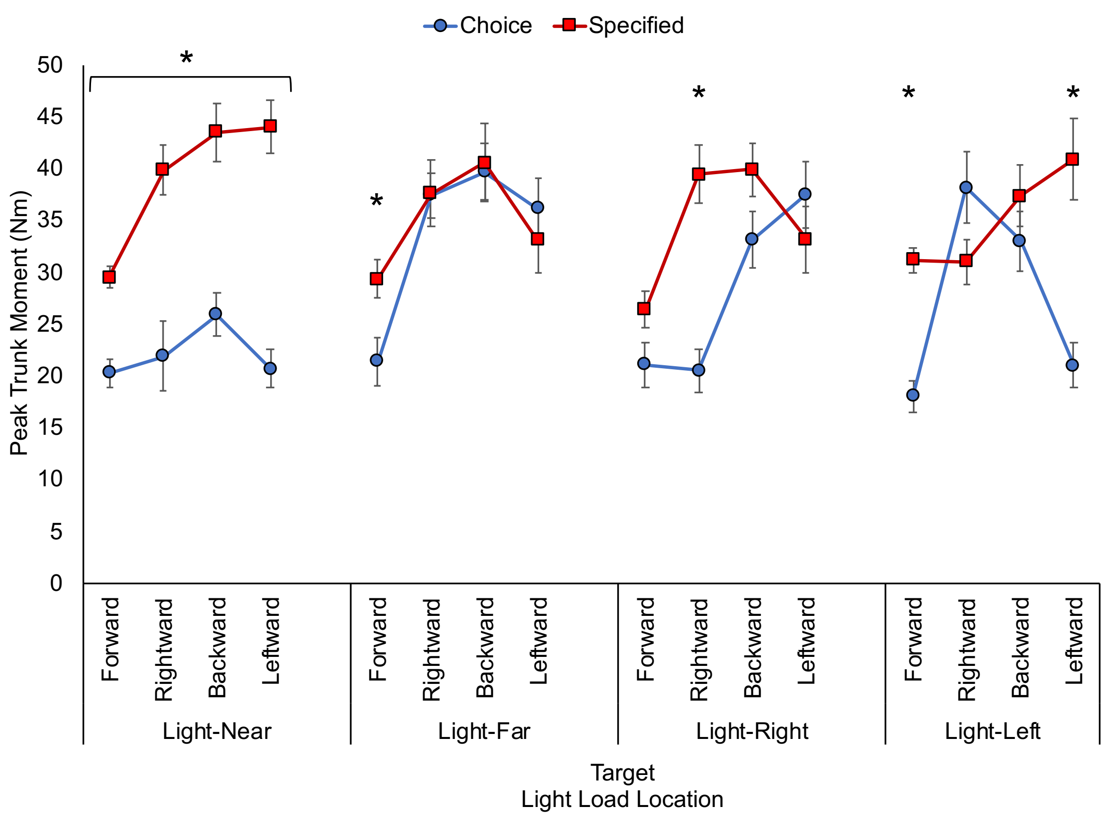


Figure 4.8 a): Interaction effect between choice, load location, and target destination on the peak trunk moment for the light variable load. Mean and standard errors are shown (n = 16). Significant differences between choice conditions are indicated by an asterisk.

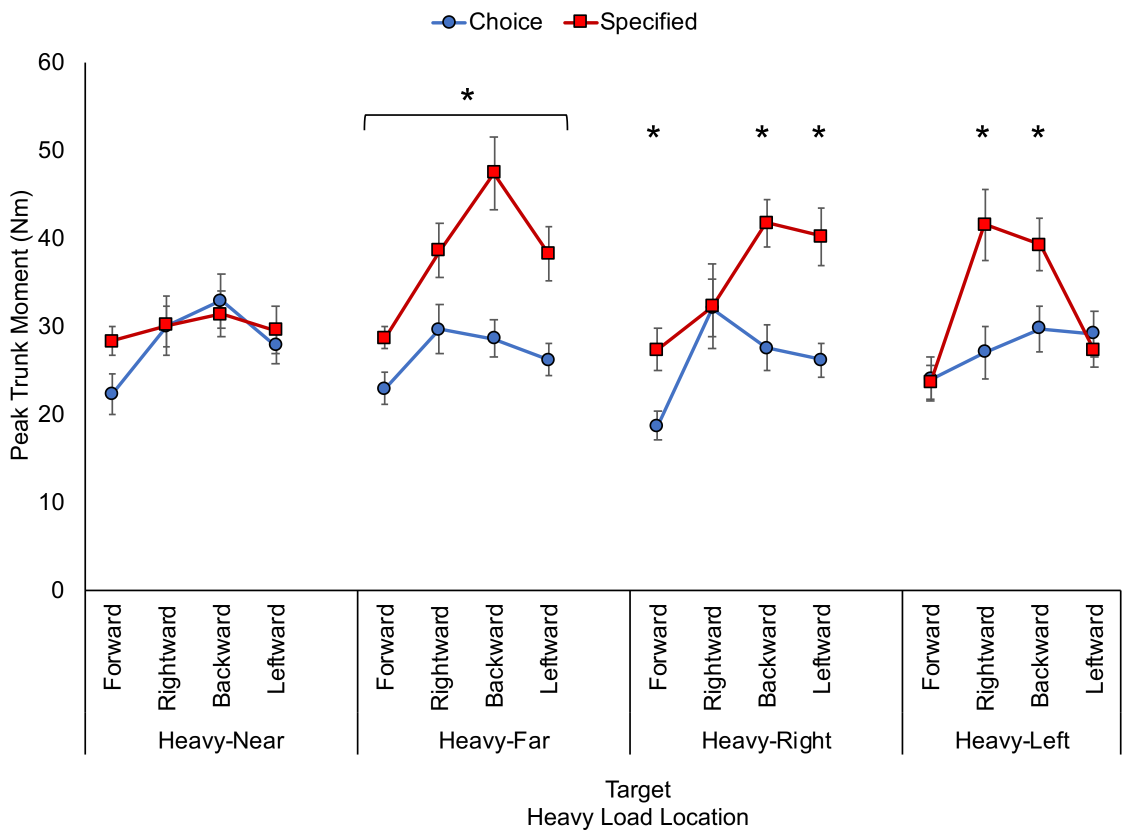


Figure 4.8 b): Interaction effect between choice, load location, and target destination on the peak trunk moment for the heavy variable load. Mean and standard errors are shown (n = 16). Significant differences between choice conditions are indicated by an asterisk.

4.4.3.4 – Cumulative Trunk Moment

There was a significant four-way interaction between load choice, variable load location, variable load magnitude, and target destination on the cumulative trunk moment, $F(2.91, 43.6) = 36.3$, $p < .0001$, $\eta_p^2 = .470$. The Greenhouse-Geiser estimate of the departure from sphericity was $\varepsilon = .323$ and was used to correct the degrees of freedom ($\chi^2(44) = 97.7$, $p < .0001$). The three-way interactions between load choice, variable load location, and target destination are shown separately for variable load magnitudes of light (Figure 4.9 a) and heavy (Figure 4.9 b). Only significant differences between chosen (block 2) and specified (block 3) trials will be noted.

4.4.3.4.1 – Light Load Variable

Light-Near: There was a 39.8% reduction in cumulative trunk moment, on average, for load transports to all target destinations when the load was selected by the participant. Light-Far: Carrying the chosen load to the forward target resulted in cumulative trunk moments that were 28.9% lower than with the specified load. Light-Right: The cumulative trunk moment was decreased by 47.6% and 21.4% when chosen loads were carried to the rightward and backward targets, respectively, compared to when specified loads were carried to the same target destinations. Light-Left: A 38.6% and 50.6% reduction in cumulative trunk moment was measured for chosen load transports to the forward and leftward targets, respectively, compared to specified load transports.

4.4.3.4.2 – Heavy Load Variable

Heavy-Near: There were no significant differences between load choice at this location. Heavy-Far: There was a 33.4% reduction in cumulative trunk moment, on average, for load transports to all target destinations when the load was selected by the participant. Heavy-Right: The cumulative trunk moment decreased by an average of 35.7% when chosen loads were carried to all target destinations except for the rightward target. <u>Heavy-Left:</u> The cumulative trunk moment was decreased by 40.2% and 28.5% when chosen loads were carried to the rightward and backward targets, respectively, compared to when specified loads were carried to the same target destinations.

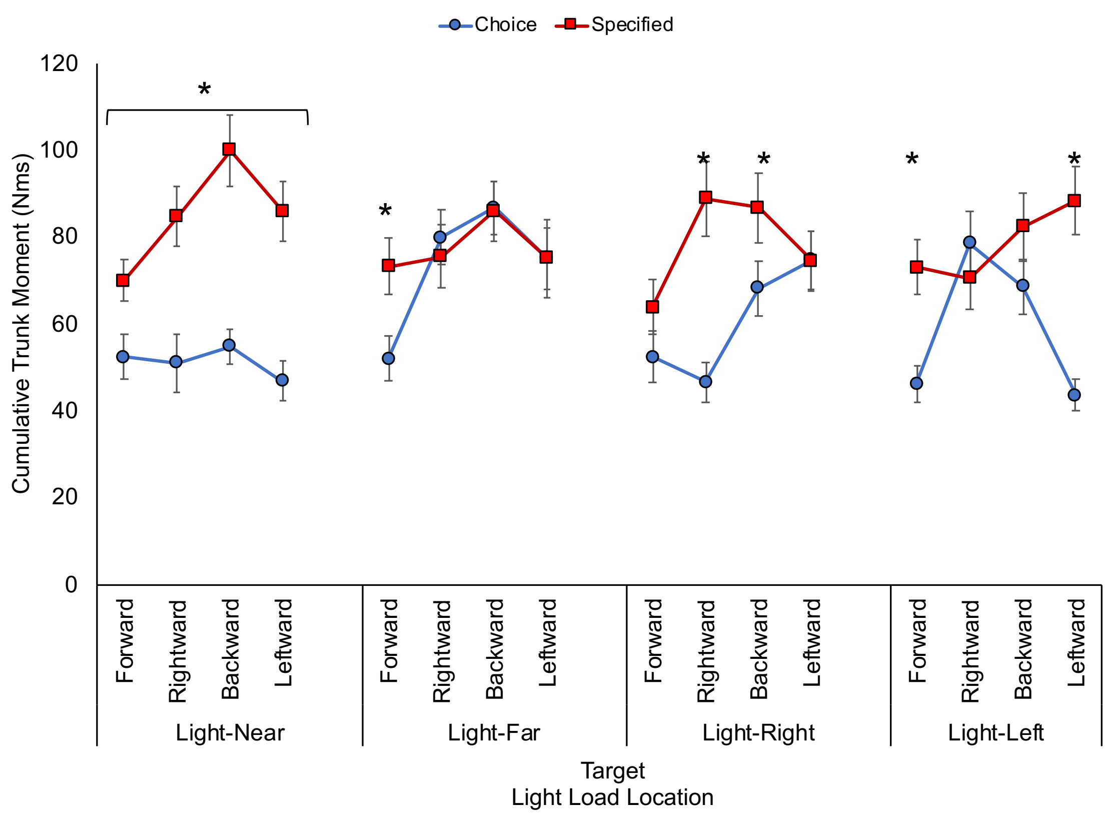


Figure 4.9 a): Interaction effect between choice, load location, and target destination on the cumulative trunk moment for the light variable load. Mean and standard errors are shown (n = 16). Significant differences between choice conditions are indicated by an asterisk.

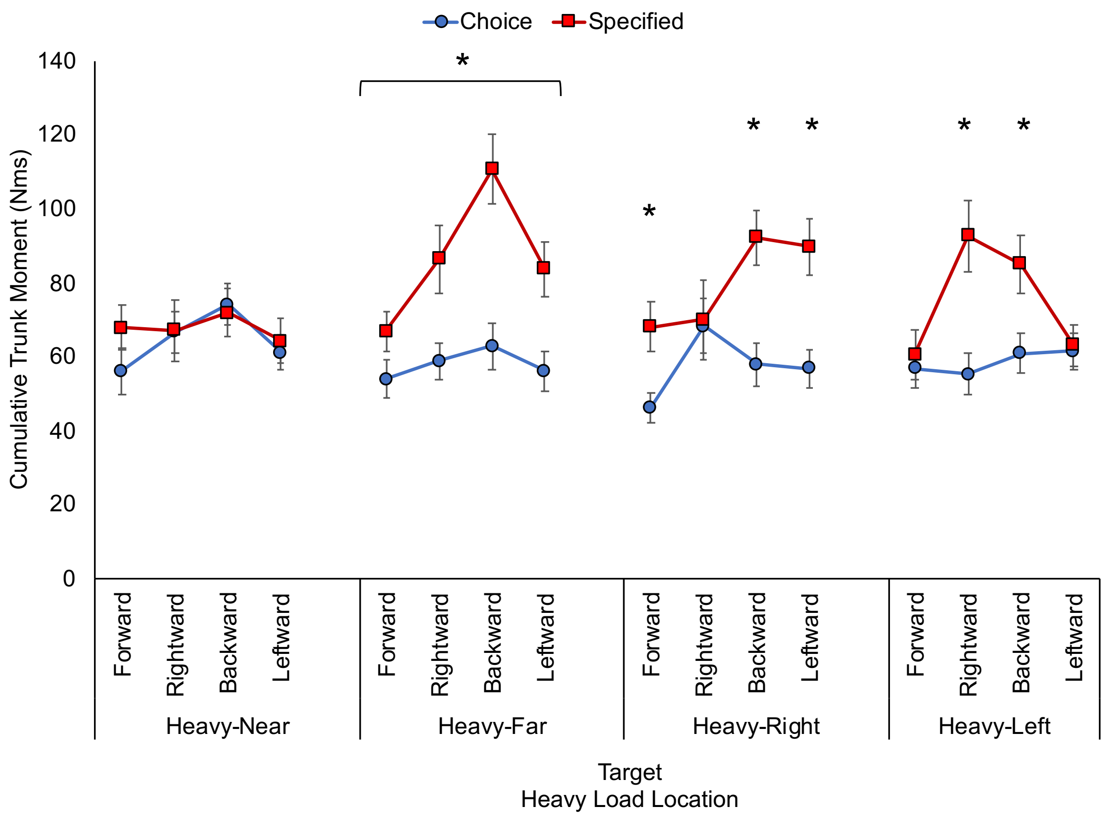


Figure 4.9 b): Interaction effect between choice, load location, and target destination on the cumulative trunk moment for the heavy variable load. Mean and standard errors are shown (n = 16). Significant differences between choice conditions are indicated by an asterisk.

4.5 – DISCUSSION

The experiment conducted in this chapter sought to examine: a) how decisions are made between tasks with differing costs in multiple domains (e.g., load and distance) and how those costs are prioritized, and b) whether functional constraints, reflected in joint loading measures, influence those choices. This was achieved by recording whole-body motion capture during task choices to obtain joint loading at the shoulder and the trunk. The most important finding of this study is that when given the choice between a light load and a heavy load, participants maintained the desire to minimize reach distance, even at the expense of carrying a load of greater magnitude, thereby confirming and also extending the results of Chapter 2 and Chapter 3. In addition, participants' self-selected load and path choices reflected conditions that exhibited significantly decreased loading compared to the load of opposite magnitude and the alternative path choices.

In free choice tasks, where both the load and target were chosen, interesting strategies emerged. For load orientations with the heavy load fixed centrally, and the light load varied to near, far, right, or left locations, predominant target choices were spatially coded to the corresponding target destination of the variable load placement. These target path choices replicated the result of the choice trials in Chapter 3. Additionally, the light load was preferred in all 4 orientations. Conversely, when the light load was fixed centrally, and the heavy load varied, the rearward target destination was preferred for all 4 load orientations. This resulted in the light load being lifted from the center location for heavy-far, heavy-right, and heavy-left arrangements. In the heavy-near arrangement, however, the heavy load was chosen most often, indicating a preference to minimize reaching and walking distance, at the expense of incurring the cost of the heavier load. These choices are harmonious with the joint loading data, where the preferred target directions yielded significantly lower peak and cumulative trunk and shoulder moments when the load was chosen compared to when it was specified.

There was one exception, however. In the heavy-near orientation, the joint loading data from target-specified trials revealed no significant differences between the moments incurred while carrying the chosen or specified loads to the backward target. This heavy-near orientation is unique in that it was the only configuration in which the probability of choosing the heavy target exceeded the probability of choosing the light target in the free choice trials (blocks 1 and 4). Thus, task conditions in which no significant difference in loading was measured are also those in which there was an increased likelihood of choosing the heavy load, consequently increasing the load demands at the shoulder and trunk. In these configurations, the heavy load was arranged in a location which minimized the reach distance compared to the location of the light load. The trade-off between choosing the closer, heavy load or the farther, light load subsequently resulted in similar costs to the motor system.

This task is unique from others in the literature that also use two loads of differing magnitude in that both loads in this study were placed centrally and allowed for an increased degrees of freedom in the actions that could be used to retrieve the preferred load. That is, in previous work, the differing magnitudes were placed along aisles on either side of the participant, constraining their load choice to be grasped only by the hand on the corresponding side, which may confound hand preferences with the other manipulated decision parameters like load magnitude, reach distance, and approach distance (Potts et al., 2018; Rosenbaum et al., 2014). In this experiment participants were afforded the freedom to use the hand of their preference for grasping and could alter reaching and walking task parameters by choosing the target destination of preference. The central load arrangement is also unique to the aisle arrangement in that the variable load imposed a constraint on the fixed, central load by acting as an obstacle. In this sense, loads may have been chosen not only to minimize horizontal reach distance, but to minimize the added cost of lifting over or around the other load.

This expansion of degrees of movement freedom allowed an opportunity for individual differences in the strategies used for task completion to emerge. One such strategy was the "walk around" movement path, whereby a participant would walk along one side of the table to retrieve the load and continue to walk around the far side of table before arriving at the target destination on the opposite side. This occurred, specifically, in load-specified, target-specified trials (block 3) where the to-be-lifted heavy load was located laterally to one side and the target destination was on the opposite side. For example, for heavy-left trials that were required to be transported to the rightward target, some participants would walk to the left side of the table so that the load could be obtained with the preferred hand and with a short reach distance, before turning 90º to walk around the far side of the table and continue to the rightward target. That is, a longer walking path was chosen to minimize the costs of the movement, consistent with Chapter 2.

Consistent with Chapter 3, there were emergent decision strategies in both load choices and target choices. Three of the 16 participants only chose to retrieve the light load magnitude, despite the added cost required to reach over/around the heavy target or by altering the movement path. Additionally, there were three participants who only chose the backward target and two more who predominantly chose the forward target, for a total of five participants who did not select any lateral target destinations when given the choice. Of those who utilized three of the four target destinations, five employed a “no backward” strategy and two employed a “no forward” strategy. Only 25% of participants (4/16) made choices to all four target destinations, compared to 63% in Chapter 3.

This observational finding, in and of itself, is important to consider. Specifically, although some degree of stereotypical behaviour typically emerges under these types of reach or walk decision scenarios, as those environments become less constrained with respect to movement options, individual differences become more evident. It is important to keep in mind that the participant pool between the experiments in Chapters 2 and 3 did not change, so even within an individual, differing task constraints and task objectives elicited a change in behaviour. Although this does not in any way diminish the overarching findings of our and other’s studies, we will be well advised to remember that “one size does not fit all”, as behaviours emerge as an interaction between the constraints of the task and the individual, as suggested by Newell (1986).

Consistent with Chapters 2 and 3, this experiment provides evidence of bottom-up processes influencing action planning, as participants prioritized decreased reach distance over bearing an increased load. These choices were also reflected in decreased joint loading in chosen versus unchosen paths at both the task shoulder and the trunk.

CHAPTER 5

GENERAL DISCUSSION

5.1 – Thesis Contributions

Redundancies in the human motor system allow movement goals to be achieved via countless combinations of those biomechanical parameters that can be used to complete a given task. These are referred to collectively as degrees of freedom. Although this allows for behaviours that are able to adapt to changes within the environment or system itself, understanding how the many degrees of freedom are organized to coordinate actions poses a challenge to movement researchers. This is particularly true when deciding between movement path options to carry out a task, such as the coordination of locomotion and grasping that are used countless times in day to day activities. This dissertation aims to address such decisions by quantifying the functional contributions to behavioural decision making in reaching and walking tasks. This was achieved through three chapters of original empirical research investigating decision making in action planning while assessing the functional costs of the executed movement choice and comparing them to the functional costs of the non-chosen movement alternative(s). The major research contributions made by the investigations of this dissertation are discussed below.

Rosenbaum and colleagues made significant advances in understanding how the costs of performing these two fundamentally distinct movements (which they often liken to the comparison of apples and oranges) are interpreted and integrated by the motor system to choose the most optimal movement path (Rosenbaum 2008, 2012; Rosenbaum et al., 2011). The second chapter of this dissertation advances the foundation of cost analysis established in the reaching and walking experiments of Rosenbaum and colleagues. Using an adaptation of methodology of Rosenbaum et al. (2011) and the task conditions of Rosenbaum (2012), Chapter 2 replicated their behavioural outcomes that revealed a predominant near-reach strategy, wherein movement paths were chosen to minimize reach distance even at the expense of increased subsequent walking distances. This strategy was organized such that when reach distances were of equal length, walking distance, as well as hand preference, were used as a secondary decision factors. Chapter 2 replicated the estimated cost of reaching, equal to 11.16 times the cost of walking the same unit distance in Chapter 2, compared to 10.2 and 11.3, in the 2011 and 2012 papers, respectively. Additionally, Chapter 2 made novel contributions to the literature by investigating the functional, mechanistic drivers which we propose act to govern these choices by comparing the demands of the shoulder and trunk in alternative path options. This research presents the such quantified accounts of functional movement costs in a decision-making task that assessed the trade-off between reaching and walking, thereby linking the biomechanical mechanisms and cognitive decision processes used in action planning.

The reaching and walking task studied in Chapter 2 imposes a high degree of constraint to the movement path choices by using a two-alternative forced choice task. The third chapter of this thesis sought to further understand how decisions are made within an environment that allows for an increased degrees of freedom of the chosen movement strategies. Using a novel four-alternative forced choice task configuration to probe the trade-off between reaching and walking, participant behaviours accounted for spatial representations of the task environment and revealed that movement choices are spatially coded from the load's start location. This task methodology assessed variants in the functional costs associated with locomotion that are introduced by factors other than walking distance, including 90º and 180º changes in walking direction. Although, choices to the backward target included these metabolically inefficient reversals in direction (McNarry et al., 2017), the backward destination was preferred for 2 of the 5 load start locations.

Finally, Chapter 4 investigated how costs of multiple task variables, such as reaching, walking, and load magnitude, are collectively integrated into action planning, and how those multiple costs sources affect the joint loading when they are directly compared to alternative strategies. This task methodology involved interactions between loads of differing magnitudes placed at varied reach distances and locations. At the time of study conceptualization and data collection, this protocol contributed a novel methodology to assess the relative contributions of both load magnitude and reach distance into choice outcomes. In this experiment, participants primarily maintained the near-reach strategy, even at the expense of bearing the increased cost of the heavier load. Thus, the near-reach strategy has been demonstrated to be a robust, emergent behavioural criterion for choosing between action alternatives in a reaching a walking task as is now evidenced by the investigations presented in this thesis and with those in the existent literature (Rosenbaum 2008, 2012; Rosenbaum et al., 2014; Potts et al., 2018 a, 2018 b). The biomechanical data presented in this dissertation provide a means to understand the functional mechanisms that may serve to support this strategy of maintaining a comfortable posture. We conclude from this that the somewhat abstract conceptualization of "comfort" can now be operationalized as maintaining a minimized joint moment throughout movement execution.

Theories of neuromotor decision-making traditionally center about two schools of thought: good-based accounts and action-based accounts. Good-based decision models combine abstract representations of the subjective value of option alternatives derived from perception into a common currency to determine the option with the highest value (Padoa-Schioppa & Assad, 2006; Padoa-Schioppa, 2011; Levy & Glimcher, 2012; Padoa-Schioppa & Conen, 2017). Once enough evidence is accumulated to favor the highest-value option, an action plan is constructed to carry out the winning option. This plan is then executed with no contributions to decision-making occurring post-movement onset (Gold & Shadlen, 2007). This account represents a rigid, serial decision process that is informed through a top-down, cognitive structure. Alternatively, action-based models represent choice alternatives via sensorimotor maps that contain information regarding the movements that can be successfully used to achieve the task goal, including object affordances and spatial representations of the environment (Cisek & Pastor-Bernier, 2014; Cisek 2007; Gallivan et al. 2018). Action-based accounts factor the predicted motor costs of movement alternatives into the decisions and provide a continuously shifting landscape of those movement costs as they progress through the duration of the movement (Cos et al. 2011; 2012; 2014). Thus, action-based models incorporate bottom-up biomechanical consequences into the decision and allow for behaviour changes after movement initiation. As the primary finding across the three empirical studies comprising this dissertation is that participant choices were made to minimize biomechanical loading incurred along the movement path, the results of this dissertation are consistent with, and provide support for action-based decision models. Another contribution of this work that is concordant with action-based accounts is that decisions within a task environment with increased degrees of freedom reflect spatial coding of movement choices that are backward planned from the task subgoal, as representations of movement interactions within the spatial configuration of the environment are considered in the decision process (Chapter 3, Chapter 4). Together, this work provides a better understanding of how environmental factors and internal representations of movement costs are used to make decisions for action.

5.2 – Limitations and Future Directions

The experiments contained that comprise this dissertation explored the relative costs associated with reaching and walking in only young, healthy female participants. Aging is associated with changes in cognitive decision-making strategies (Brown & Ridderinkof, 2009; Sporten et al., 2018) as well as declines in functional capabilities (Doherty, 2001; Schiffman et al., 1992), and altered gait control (Aboutorabi et al., 2016; Al-Yahya et al., 2011; Beauchet et al., 2003; Preist et al., 2008). Therefore, the relative costs associated with reaching and walking would likely reflect age-related changes to coordination and control movement. Thus, the hierarchical organization of movement costs in a decision task within an aging population may be different from those reported here. An investigation comparing path selection, movement strategies, and relative contributions of movement costs in a younger versus older population would be a valuable avenue for future research.

Another limitation to these experiments is in the use of absolute, rather than relative, task loads which may have biased participant behaviour, dependent on individual strength. All participants performed the bucket transfer tasks with either 1.3 kg (Chapter 2, 3, 4) or 3.9 kg (Chapter 4) load magnitudes. As participant strength data was not measured in this study, these magnitudes likely represent different percentages of each participants maximum strength. Participants in which the loads accounted for a greater percent of maximum likely internalized the costs of the loads differently than participants with greater absolute strength, which may have impacted the resulting behavioural strategies. There were three participants in Chapter 4 who only chose the light load and avoided the heavy load until it was specified to be chosen. It is possible that the heavy load magnitude accounted for a greater proportion of these participant's strength capacity, influencing their choices.

It is important to consider that although efforts were made to provide naturalistic choice outcomes, participants *had* to make a decision in the experimental choice trials, and those decisions *had* to conform to one of the allocated response options. It is possible, however, that there may exist task situations in which the preferred mode of action, or even the preferred target destination, fell outside the range of those response options tested in this work. It is also quite possible, and ecologically valid, to acknowledge that not choosing to elicit a response at all would be an element among the subset of participant response strategies.

Lastly, only joint moment data from the task shoulder and the trunk were analyzed and reported in this document. It has been suggested that the near-reach strategy is predominantly chosen to minimize the leaning distance needed to grasp a load in a contralateral or far location (Rosenbaum 2008; Rosenbaum et al. 2011). Therefore, these joints of interest were chosen for investigation a priori because of their involvement in the adaptive postural strategy needed to extend the functional reach distance of the arm when retrieving a far load. Analyzing the changes in loading at other joints (e.g. hips, knees, or ankles) between chosen and non-chosen movement alternatives may provide further insights to the contributions and influence of functional movement demands on action planning in a decision-making task.

5.3 – Application

The results of this dissertation can be used to model and predict behavioural outcomes in tasks that require a choice to be made involving the relative contributions of walking, reaching, and carrying behaviours. Having the capacity to accurately predict human behaviour becomes advantageous in applications such as Ergonomics, where considerations of human interactions within a task environment can be used in proactive analyses that simulate the work process early in the design phase. By immersing a digital human model within a proposed workspace and having it behave as a worker would, injury risk can be assessed, providing a cost effective method of way of reducing worker injury rates long before the workstation physically exists (Chaffin, 2002; Chaffin, 2005; Colombo & Cugini, 2005).

In an industrial setting, this type of technology, such as Jack Static Strength Prediction, is heavily relied on when designing tasks, however the prediction of worker behaviour is not fully automated yet. This leads to a large degree of inter-user variability, since ergonomists must use their judgment and experience to posture and manipulate the manikins within the simulated environment (Dukic et al., 2007; Lamkull et al., 2007; McInnis et al., 2009; Savin, 2011). Even subtle differences in the way the manikins are postured can lead to significantly different results for joint angles and population strength estimates, which have the potential to lead to incorrect decisions being made about whether a job is acceptable or not (McInnis et al., 2009; Chaffin, 2002). The results of this dissertation contribute to the understanding of how postures for action are selected by quantifying internal demands during task alternatives and demonstrating that actions are chosen in effect to minimize joint demands. Integrating these data, which account for physical and cognitive factors underlying posture selection, will aid in both the understanding and prediction of these behaviours, which will likely serve to improve the accuracy of, and reduce the variability associated with, the person performing the assessment.

Collectively, this research provides a deeper understanding of the functional mediators of hierarchical movement planning and this can be applied to the prediction and simulation of occupational tasks. Ultimately, by understanding the decision-making processes involved when interacting with a workspace with predetermined environmental constraints (e.g. reaching and walking distances), the outcomes of this research can be used to develop guidelines for the ergonomic design of workspaces, as well as improve posture prediction software, so that work can be simulated with a high degree of behavioural fidelity. Ultimately, this will allow for the creation of safer jobs proactively, which, in turn, will decrease the risk of injury for workers.

5.4 – Summary

The original empirical research presented within this thesis investigates how decisions are chosen between action alternatives, and compares the functional costs mediating these decisions. This work provides a better understanding of how environmental factors and internal representations of movement costs are used to make decisions for action. The investigations in this dissertation have made novel contributions to the literature by quantifying the functional movement costs in a decision-making task that integration of reaching and walking costs linking the bottom-up biomechanical mechanisms with top-down cognitive processes used in action planning. This is significant in that it provides evidence that movements are chosen in effect to minimize the loading costs incurred at the shoulder and trunk during tasks with a differential reaching distance.

6.0 – REFERENCES

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APPENDIX A: Certificate of Ethics Clearance from the McMaster Ethics Review Board (MREB)

McMaster University
Inspiring Innovation and Discovery

McMaster University Research Ethics Board (MREB)

c/o Research Office for Administrative Development and Support, MREB Secretariat, GH-305, e-mail: ethicsoffice@mcmaster.ca

CERTIFICATE OF ETHICS CLEARANCE TO INVOLVE HUMAN PARTICIPANTS IN RESEARCH

Application Status: New ☑ **Addendum** ☐ **Project Number:** 2017 220

TITLE OF RESEARCH PROJECT:

Quantifying the biomechanical costs used to make behavioural decisions when choosing between action plans

Faculty Investigator(s)/ Supervisor(s)	**Dept./Address**	**Phone**	**E-Mail**
J. Lyons	Kinesiology		lyonsjl@mcmaster.ca
Co-Investigators/ Students	**Dept./Address**	**Phone**	**E-Mail**
J. Cappelletto	Kinesiology		cappelja@mcmaster.ca

The application in support of the above research project has been reviewed by the MREB to ensure compliance with the Tri-Council Policy Statement and the McMaster University Policies and Guidelines for Research Involving Human Participants. The following ethics certification is provided by the MREB:

☐ The application protocol is cleared as presented without questions or requests for modification.
☑ The application protocol is cleared as revised without questions or requests for modification.
☐ The application protocol is cleared subject to clarification and/or modification as appended or identified below:

COMMENTS AND CONDITIONS: Ongoing clearance is contingent on completing the annual completed/status report. A "Change Request" or amendment must be made and cleared before any alterations are made to the research.

Reporting Frequency:	**Annual:** Dec-11-2018	**Other:**

Date: Dec-11-2017 **Chair, Dr. S. Bray**

APPENDIX B: Participant Informed Consent form used in Chapter 2

DATE: ____________________

McMaster University
Inspiring Innovation and Discovery

Quantifying the biomechanical costs used to make behavioural decisions when choosing between action plans

Principal Investigator:
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Purpose of the Study: The study is designed to examine how humans make decisions between possible action alternatives within an environment.

Who is eligible to participate? I am looking for participants who re right-handed females between the age of 18 and 35 and have not had any upper limb or upper body injuries within the last year.

Procedures involved in the Research: You will be asked to walk to a table to retrieve a bucket and then place it on a target. There are two possible targets in each trial. It is up to you to decide which target you place the bucket on, and to do so in the most natural or comfortable manner possible. You can use either hand to complete this task. The bucket weighs 1 kg, and you will be allowed to familiarize yourself with the weight before the trials commence. The total walking distance of each trial will range between 3 and 8 metres. You will complete a total of 30 trials. You will be able to proceed at your own pace and may take rest breaks, as you need them.

Inertial kinematic sensors will be used to record the movement of your body during each trial. Fifteen motion sensors will be fixed onto various parts of your body using Velcro straps placed over your clothing in the following locations: pelvis, arms, hands, legs, feet, and head. The lead investigator, Jessica, will need to affix these sensors to your body which requires some bodily contact. The sternum and shoulder motion sensors are attached to a zippered shirt that you can wear over your own clothing. There will be no camera recording of you during the experiment. This motion capture technology is widely used for research purposes and in the making of sports video games and animated movies. To ensure proper placement of the sensors, you are asked to wear comfortable shoes, a form-fitting tank top, and leggings or shorts during the experimental session.

The following personal information will be measured and recorded: age, height, ankle height, knee height, hip height, shoulder height, shoulder width, hip width, arm span, body weight.

Compensation and Right to Withdraw: Your participation in this study is completely voluntary and you are free to withdraw at any time during the experimental protocol without any consequences. If after participation, you wish to withdraw, please contact the investigators within one week. If you choose to withdraw, your data will be discarded, unless you indicate otherwise. You will receive a $10 honorarium for completing the experimental session.

***Potential Risks and Benefits*:** The motion sensors will need to be applied in the following locations: R hand, R forearm, R upper arm, R shoulder, L hand, L forearm, L upper arm, L shoulder, head, sternum, pelvis, R thigh, R shank, R foot, L thigh, L shank, L foot. The lead investigator, Jessica, will be attaching these to your body using Velcro straps. In addition, some sensitive personal information such as your age, body measurements, and weight will be recorded. If you do not feel comfortable with these procedures please let Jessica know and you are free to withdraw your participation.

During the experimental protocol, you will be lifting a 1kg weight and transferring it to one of the target locations. The conditions and trials will occur within a fairly short time frame, and you may experience some mild soreness in the muscles of the hand and arm the next day, but this should be no more than would be experienced after any unaccustomed physical activity. If you feel tired or experience any extreme discomfort, you can stop the testing.

The data collected in this study will be used as part of Jessica Cappelletto's PhD dissertation. Although there will be no direct benefits to you, the study will have a lot of practical and theoretical applications in the field of Ergonomics and Motor Control. Benefits of participating in the study would be to experience first hand some of the methods and procedures used in conducting cognitive ergonomics research.

***Confidentiality*:** The data collected in this study will be used as part of Jessica Cappelletto's PhD dissertation. The results of her study will be made public when her thesis is published online. Only average values off all the participants will be presented in any published works, no individual participant data. Your participation in this study is completely confidential. During your participation in the research study, only the lead investigator Jessica and a research assistant will be present in the room. Once your participation is complete, no identifying information (i.e. your name) will be used when discussing the findings of this study. To ensure this, you will be assigned a randomly generated subject code known only to the investigators and therefore your identity cannot be determined by anyone other than the investigators. Your personal information including age, physical characteristics (such as your body measurements and weight) will be kept anonymous on all documents using the coding system. All written documentation, including this letter, will be kept for 7 years in a locked filing cabinet within IWC AB104 before being securely destroyed. Anonymized data including your age, body measurements, weight, and movement data will be stored on a password-protected computer in IWC AB104 until the study is completed. Once complete, the data will be transferred to Dr. Jim Lyons locked office for safe storage.

Questions about the Study: If you have questions or need more information about the study itself, please contact any of the associated investigators. Each of the investigators is listed, along with their contact information, at the beginning of this document.

Information about the Study Results: We expect to have this study completed by May 2018. You may obtain information about the results of the study by contacting one of the investigators or by leaving your email address below so that the final results will be forwarded to you. Study results will also be making public when Jessica's PhD dissertation is complete, expected by September 2018.

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

McMaster Research Ethics Secretariat
Telephone: (905) 525-9140 ext. 23142
c/o Research Office for Administrative Development and Support
E-mail: ethicsoffice@mcmaster.ca

CONSENT

- I have read the information presented in the information letter about a study being conducted by Jessica Cappelletto
- I have had the opportunity to ask questions about my involvement in this study and to receive additional details I requested.
- I understand that if I agree to participate in this study, I may withdraw from the study at any time during the data collection process
- I have been given a copy of this form.
- I agree to participate in the study

Signature: ______________________________

Name of Participant (Printed): ____________________________

E-mail (Only if you would like to receive the study results): _______________________

APPENDIX C: Participant Informed Consent form used in Chapter 3

DATE: ____________________

Quantifying the biomechanical costs used to make behavioural decisions when choosing between action plans

Principal Investigator:
Jessica Cappelletto
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Hamilton, Ontario, Canada
(905) 541- 4534
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Supervisor:
Dr. Jim Lyons
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Hamilton, Ontario, Canada
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Purpose of the Study: The study is designed to examine how humans make decisions between possible action alternatives within an environment.

Who is eligible to participate? I am looking for participants who re right-handed females between the age of 18 and 35 and have not had any upper limb or upper body injuries within the last year.

Procedures involved in the Research: You will be asked to walk to a table to retrieve a bucket and then place it on a target. There are 4 possible targets in each trial. In some trials, it is up to you to decide which target you place the bucket on, and to do so in the most natural or comfortable manner possible. In other trials, the target will be specified for you. You can use either hand to complete this task. The bucket weighs 1.3 kg, and you will be allowed to familiarize yourself with the weight before the trials commence. The total walking distance of each trial will range between 4 and 9 metres. You will complete a total of 50 trials. You will be able to proceed at your own pace and may take rest breaks, as you need them.

Inertial kinematic sensors will be used to record the movement of your body during each trial. Fifteen motion sensors will be fixed onto various parts of your body using Velcro straps placed over your clothing in the following locations: pelvis, arms, hands, legs, feet, and head. The lead investigator, Jessica, will need to affix these sensors to your body which requires some bodily contact. The sternum and shoulder motion sensors are attached to a zippered shirt that you can wear over your own clothing. There will be no camera recording of you during the experiment. This motion capture technology is widely used for research purposes and in the making of sports video games and animated movies. To ensure proper placement of the sensors, you are asked to wear comfortable shoes, a form-fitting tank top, and leggings or shorts during the experimental session.

The following personal information will be measured and recorded: age, height, ankle height, knee height, hip height, shoulder height, shoulder width, hip width, arm span, body weight.

Compensation and Right to Withdraw: Your participation in this study is completely voluntary and you are free to withdraw at any time during the experimental protocol without any consequences. If after participation, you wish to withdraw, please contact the investigators within one week. If you choose to withdraw, your data will be discarded, unless you indicate otherwise. You will receive a $10 honorarium for completing the experimental session.

***Potential Risks and Benefits*:** The motion sensors will need to be applied in the following locations: R hand, R forearm, R upper arm, R shoulder, L hand, L forearm, L upper arm, L shoulder, head, sternum, pelvis, R thigh, R shank, R foot, L thigh, L shank, L foot. The lead investigator, Jessica, will be attaching these to your body using Velcro straps. In addition, some sensitive personal information such as your age, body measurements, and weight will be recorded. If you do not feel comfortable with these procedures please let Jessica know and you are free to withdraw your participation.

During the experimental protocol, you will be lifting a 1kg weight and transferring it to one of the target locations. The conditions and trials will occur within a fairly short time frame, and you may experience some mild soreness in the muscles of the hand and arm the next day, but this should be no more than would be experienced after any unaccustomed physical activity. If you feel tired or experience any extreme discomfort, you can stop the testing.

The data collected in this study will be used as part of Jessica Cappelletto's PhD dissertation. Although there will be no direct benefits to you, the study will have a lot of practical and theoretical applications in the field of Ergonomics and Motor Control. Benefits of participating in the study would be to experience first hand some of the methods and procedures used in conducting cognitive ergonomics research.

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Signature: ______________________________

Name of Participant (Printed): ____________________________

E-mail (Only if you would like to receive the study results): _________________________

APPENDIX D: Participant Informed Consent form used in Chapter 4

DATE: ____________________

Quantifying the biomechanical costs used to make behavioural decisions when choosing between action plans

Principal Investigator:
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Supervisor:
Dr. Jim Lyons
Professor
Department of Kinesiology
Hamilton, Ontario, Canada
(905) 525- 9140 ext. 27899
E-mail: (lyonsjl@mcmaster.ca)

Purpose of the Study: The study is designed to examine how humans make decisions between possible action alternatives within an environment.

Who is eligible to participate? I am looking for participants who are right-handed females between the age of 18 and 35 and have not had any upper limb or upper body injuries within the last year.

Procedures involved in the Research: You will be asked to walk to a table to retrieve a bucket and then place it on a target. There are 4 possible targets in each trial. In some trials, it is up to you to decide which target you place the bucket on, and to do so in the most natural or comfortable manner possible. In other trials, the target will be specified for you. You can use either hand to complete this task. There are two buckets to choose from, one bucket weighs 1.3 kg and the other weighs 3.9 kg. You will be able to familiarize yourself with the weights before the trials commence. The total walking distance of each trial will range between 4 and 9 metres. You will complete a total of 80 trials. You will be able to proceed at your own pace and may take rest breaks, as you need them.

Inertial kinematic sensors will be used to record the movement of your body during each trial. Fifteen motion sensors will be fixed onto various parts of your body using Velcro straps placed over your clothing in the following locations: pelvis, arms, hands, legs, feet, and head. The lead investigator, Jessica, will need to affix these sensors to your body which requires some bodily contact. The sternum and shoulder motion sensors are attached to a zippered shirt that you can wear over your own clothing. There will be no camera recording of you during the experiment. This motion capture technology is widely used for research purposes and in the making of sports video games and animated movies. To ensure proper placement of the sensors, you are asked to wear comfortable shoes, a form-fitting tank top, and leggings or shorts during the experimental session.

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Signature: ______________________________

Name of Participant (Printed): ____________________________

E-mail (Only if you would like to receive the study results): ________________________

APPENDIX E – ANOVA results for Chapter 2

List of p-values of each effect tested for the biomechanical variables of Chapter 2, conducted by a 2x3x5 repeated measures ANOVA. Effect sizes (η^2) are shown in parentheses. Significant effects (p<.05) are displayed within a yellow cell. Significant effects that also account for more than 1% of the variance (η^2 > .01) are shown in bold-face type. The highest-level significant effects for each dependent variable are shown in red and are discussed in Chapter 2.4.

Effect	**Dependent Variables**			
	Peak Shoulder Moment	Cumulative Shoulder Moment	Peak Trunk Moment	Cumulative Shoulder Moment
Choice	**0.0001 (0.264)**	**0.0001 (0.149)**	**0.0001 (0.276)**	**0.0001 (0.140)**
Load Location (LL)	0.456 (0.007)	0.105 (0.007)	**0.0001 (0.130)**	**0.0001 (0.070)**
Differential Target Distance (D_t)	0.275 (0.005)	**0.0001 (0.098)**	0.601 (0.002)	**0.0001 (0.035)**
Choice*LL	**0.0001 (0.157)**	0.001 (0.078)	**0.0001 (0.189)**	**0.0000 (0.137)**
Choice* D_t	0.486 (0.007)	**0.065 (0.016)**	0.55 (0.003)	0.766 (0.002)
LL* D_t	0.617 (0.005)	**0.305 (0.011)**	0.784 (0.002)	0.767 (0.004)
Choice*LL* D_t	**0.159 (0.023)**	**0.0001 (0.111)**	**0.014 (0.036)**	**0.0001 (0.109)**

APPENDIX F – ANOVA results for Chapter 3

List of p-values of each effect tested for the biomechanical variables of Chapter 3, conducted by a 5x4 repeated measures ANOVA. Effect sizes (η^2) are shown in parentheses. Significant effects (p<.05) are displayed within a yellow cell. Significant effects that also account for more than 1% of the variance (η^2 > .01) are shown in bold-face type. The highest-level significant effects for each dependent variable are shown in red and are discussed in Chapter 3.4.

Effects	**Dependent Variables**			
	Peak Shoulder Moment	Cumulative Shoulder Moment	Peak Trunk Moment	Cumulative Trunk Moment
Start Location	**0.0001 (0.164)**	**0.0001 (0.084)**	**0.0001 (0.190)**	**0.0001 (0.198)**
Target	**0.01 (0.074)**	**0.1336 (0.041)**	**0.0001 (0.306)**	**0.0001 (0.277)**
Start*Target	**0.0001 (0.144)**	**0.0001 (0.270)**	**0.0001 (0.813)**	**0.0001 (0.257)**

APPENDIX G – ANOVA results for Chapter 4

List of p-values of each effect tested for the biomechanical variables of Chapter 4, conducted by a 2x4x2x4 repeated measures ANOVA. Effect sizes (η^2) are shown in parentheses. Significant effects (*p*<.05) are displayed within a yellow cell. Significant effects that also account for more than 1% of the variance ($\eta^2 > .01$) are shown in bold-face type. The highest-level significant effects for each dependent variable are shown in red and are discussed in Chapter 4.4.

Effect	**Dependent Variables**			
	Peak Shoulder Moment	Cumulative Shoulder Moment	Peak Trunk Moment	Cumulative Shoulder Moment
Choice	**0.0002 (0.161)**	**0.0004 (0.143)**	**0.0000 (0.132)**	**0.0001 (0.196)**
Load Location (LL)	0.0015 (0.002)	0.0014 (0.005)	**0.0001 (0.016**	**0.0001 (0.016)**
Load Magnitude (LM)	0.0497 (0.000)	0.9805 (0.000)	0.0099 (0.004)	0.0403 (0.002)
Target Destination	0.1707 (0.002)	0.0140 (0.005)	**0.0001** (0.157)	**0.0001 (0.097)**
Choice*LL	0.6356 (0.003)	0.1345 (0.002)	0.1416 (0.003)	0.2560 (0.001)
Choice*LM	0.1657 (0.000)	0.5706 (0.000)	0.0341 (0.000)	0.5703 (0.000)
Choice*Target	**0.0009 (0.020)**	**0.0011 (0.021)**	0.5422 **(0.001)**	0.1762 (0.004)
LL*LM	0.0660 (0.001)	0.6178 (0.000)	0.6277 (0.001)	0.6287 (0.000)
LL*Target	0.1646 (0.001)	0.0121 (0.004)	**0.0001** (0.016)	**0.0001 (0.018)**
LM*Target	0.2850 (0.000)	0.6183 (0.000)	0.1688 (0.002)	0.5864 (0.001)
Choice*LL*LM	**0.0001 (0.123)**	**0.0002 (0.093)**	**0.0001 (0.049)**	**0.0001 (0.058)**
Choice*LL*Target	0.0500 (0.009)	0.1376 (0.007)	0.0333 (0.008)	0.3061 (0.004)
Choice*LM*Target	**0.0071 (0.010)**	**0.0011 (0.017)**	0.0606 (0.003)	0.0526 (0.004)
LL*LM*Target	0.0941 (0.002)	0.0991 (0.003)	0.3043 (0.002)	0.6376 (0.001)
Choice*LL*LM*Target	**0.0001 (0.121)**	**0.0001 (0.114)**	**0.0001 (0.079)**	**0.0001 (0.087)**