POSTURAL AND MANUAL CONTROL DURING CONSTRAINED TASKS

by

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A Dissertation

Submitted to the Faculty of Purdue University

In Partial Fulfillment of the Requirements for the degree of

Doctor of Philosophy

Department of Health and Kinesiology

West Lafayette, Indiana

May 2021

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For my Parents and my Husband

ACKNOWLEDGMENTS

Special thanks to my advisor Dr. Jeffrey Haddad for his pieces of advice, professional guidance, and countless discussions and useful critiques during the past six years.

I would like to express my appreciation to my dissertation committee, Dr. Jeffrey Haddad, Dr. Satyajit Ambike, Dr. Howard Zelaznik, and Dr. Hong Tan for their helpful insights and recommendations.

I would like to especially thank Dr. Satyajit Ambike for supporting and teaching me advanced analyses.

I would also like to extend my thanks to the Department of Health and Kinesiology for offering me the resources to complete my Ph.D., this project, and the funding to present my work at some conferences.

I thank my lab mates for stimulating discussions and everyone that participated in this study.

Lastly, I wish to thank my mom and dad, for their support, encouragement, and understanding throughout my study and my life. I thank my husband, who supported me patiently in my last year of Ph.D.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABREVIATIONS

DOF =	Degrees of freedom
UCM =	Uncontrolled manifold hypothesis
Vucm =	Variability in UCM space
Vort =	Variability in orthogonal space
DVz =	Z-transformed index of synergy
CoP =	Center of pressure
CoM =	Center of mass
SD =	Standard deviation
DTC =	Dual task cost

ABSTRACT

The concurrent control of both standing and manual tasks are sophisticated since redundant, mechanically linked degrees of freedom (DOF) must be coordinated by a control strategy in a manner that affords completion of both tasks (Berret, Chiovetto, Nori, & Pozzo, 2011). In previous studies, a flexible control strategy was typically adopted and presented as the best behavior in the young adults in a task with only a manual task challenge (Kim et al., 2012) or postural task demand (Reisman et al., 2002). For the first study, we argued the flexible control strategy is the byproduct of experimental design with minimal challenge. When both manual and postural tasks are challenging, the motor system may adopt a less flexible control strategy to coordinate joint angles. We aimed in the first study to show that a less flexible control strategy can adapt to the challenges of a postural manual task in young adults. Twelve healthy participants (25 ± 4.2 years) performed a fitting task that required a small block to be transported, fitted, and held in a small or large opening for five seconds while standing on a narrow or wide surface. In addition to the uncontrolled manifold (UCM) analysis (variability spanned in the UCM space (Vucm), orthogonal space (Vort), and coordination metric (DVz) for hand and CoM control, we determined the hand and CoM standard deviation (SD) on 20 error-free trials (no block contact with the opening and no tilting of the surface). We found higher CoM and hand SD as well as invariant CoM and hand Vucm imposed by the narrow surface, which resulted in a reduction of joint-angle variability (less flexible control strategy) while holding a block in the small or large opening. The smaller CoM and hand SD, and greater Vucm, suggested a more flexible control strategy was adopted when standing on a wide surface and attempting the action of fitting the block to the small opening. The strength of the control strategy remained high across these conditions (high DVz). We concluded that a flexible control strategy is not a ubiquitous movement strategy in young adults (at both levels

of coordinating joint angles and the variability of end effectors). We argued that the postural constraint (i.e., standing on the narrow surface) is the driving factor in the control strategy throughout a postural manual task. The immobilization of joints and muscle co-contraction were discussed that facilitated the postural task priority. The consequence of postural constraint (i.e., falling) appeared to increase the notion of postural control and explained our findings. Thus, in the first study, we inferred the consequences associated with the tasks (falling and losing precision) might induce higher priority for one task. The direct examination of the task prioritization was investigated in the second study.

In the second study, we examined task prioritization in a postural manual task. This specific paradigm was chosen because both manual and postural tasks can have consequences if they are not performed properly. In previous studies, posture is often considered to have priority over the concurrent performance of other tasks (Bloem et al., 2002). However, both postural and manual tasks can have consequences if they are executed poorly. The consequences of not performing a task appropriately can influence how the nervous systems prioritizes the individual component tasks. Typically, if one task, such as posture, is prioritized, other concurrent tasks' performance can decline (Shumway et al., 1997). Additionally, task prioritization may have influenced the adoption of the control strategy observed in our previous study. The emergence of a less flexible control strategy may be associated with postural prioritization while standing on a narrow surface since safety and balance was important during this condition. In contrast, the flexible control strategy may have signaled manual prioritization while standing on a wide support surface and fitting a block to a small opening. In the second study, the main objective was to investigate how changing postural and manual task constraints determines task prioritization. Participants performed a postural manual task while standing on a wide or narrow surface and fitting a block to a small or large opening. We examined whether the postural or manual task was prioritized by calculating a dual-task cost (DTC) for the center of pressure (CoP) and hand variability. When participants were standing on the wide-support surface and fitting to the small opening, the hand and CoP Variability DTC were not significantly different, signifying no task priority. In contrast, higher hand Variability DTC than CoP Variability DTC when standing on the narrow surface in a condition with or without a manual challenge (fitting to either small or large opening) exhibited higher postural priority. Therefore, it appears that balance is prioritized over manual control when the postural task has consequences with higher hazard estimation.

Overall, my dissertation has extended a comprehensive understanding of the task-specific behavior of control strategy in the postural manual task, and how posture is prioritized when consequences of performing both postural and manual tasks are varied.

CHAPTER 1. INTRODUCTION

1.1 Statement of the problems

Performing a standing manual task requires coordination of redundant and mechanically linked degrees of freedoms (DOF) (Morasso, Casadio, Mohan, & Zenzeri, 2010). This redundancy results in an abundance of motor solutions to coordinate a control strategy. The behavior of the control strategy is complicated, given the individual is attempting to complete both postural and manual tasks (Hilt, Berret, Papaxanthis, Stapley, & Pozzo, 2016; Morasso et al., 2010; Pozzo, Stapley, & Papaxanthis, 2002).

The nervous system can utilize various control strategies when performing complex movements. In studies with a single task constraint, a flexible control strategy is often considered to be optimal and frequently observed in younger adults. In contrast, a less flexible control strategy is often observed in older adults (Hsu et al., 2014) or in people with motor disorders (Falaki et al., 2016). A control strategy is considered flexible when there is a high variation among DOF, which are utilized adaptively to ensure task performance (Goodman et al., 2005). In a flexible control strategy, the high covariation among DOF is used to counteract the movement variability that occur at the level of the individual DOF (Freitas et al., 2010). This strategy inevitably creates a variety of possible trajectories by the joints to complete the task and is, therefore, considered a more adaptive strategy. In the flexible control strategy, the central nervous system try to complete motor tasks in different ways (Goodman, Shim, Zatsiorsky, & Latash, 2005). For example, when only manual task was challenging, a flexible control strategy was observed when standing on a stable surface and reaching (Solnik et al., 2013), pointing to targets of different sizes (Kim et al., 2012), or standing and laser targeting with ball balancing (Hsu & Scholz, 2012). Flexible control has also been observed when only standing was challenged over a narrow surface, for example, in standing and load-pushing task (Wang & Asaka, 2008).

Consequently, a less flexible strategy is when DOF covariation is constrained, resulting in stiffness and a reduction in individual joint flexibility (Latash et al., 2007). Technically, a less flexible control strategy has the advantage of utilizing specific mathematical solutions to the problem of kinematic redundancy; therefore, this may exploit just enough variability among DOF to achieve stable control of the end effectors (Bernstein, 1967; Hsu et al., 2014; Latash et al., 2007). In a less flexible control strategy, movements of the body are easier to control but less adaptable since possibilities for movement are reduced, resulting in a reduced ability to attenuate perturbations or perform in a dynamic environment.

Typically, in young adults performing an easy task with a minimal challenge (e.g., a task with minimal constraints), a flexible control strategy would be observable. For example, when performing a relatively easy task (pointing) while standing on a stable surface, young adults exhibit high flexibility (Solnik et al., 2013). Young adults also appear to exhibit high flexibility when performing manual tasks with single task constraints (e.g., a manual only or standing only task), even as the constraints become more difficult. For example, if a young adult performs a task with manual constraints such as pointing a laser and balancing a ball on a tray (Hsu & Scholz, 2012), or standing on a narrow surface continuously for 20 seconds, young adults adopt a flexible control strategy (Hsu et al., 2014).

However, the idea that a more flexible control strategy is ubiquitous and always observed in young adults is not always the case. Rather, the specific strategy utilized depends to a large extent on the task constraints, as well as the consequences of failure (e.g., falling). In difficult tasks with dual constraints (e.g., adopting a difficult posture while reaching for an object), allowing a flexible control strategy with extraneous and variable movements among DOF (e.g., joint angles) may result in task failure. In such a case, adopting a less flexible strategy may be more optimal since variable movements may be more difficult to control. Additionally, consequences associated with task failure may cause the utilization of a less flexible strategy. In such a case, a less flexible control strategy, although less adaptable, may be more controllable and minimize the chance of producing a self-generated perturbation. How the nervous system adopts control strategies when performing a posture and manual task with varying constraints has not been examined. Studying such control strategies is essential since many common tasks are performed while standing, and task failure can result in a fall.

Movement control strategies have primarily been investigated using the UCM analysis (Latash et al., 2002; Scholz & Schöner, 1999). The UCM examines the structure of variability among DOF (Freitas et al., 2010; Latash et al., 2002; Scholz & Schöner, 1999; Scholz et al., 2000). Based on the UCM hypothesis, the controller coordinates the joints by the use of two types of covariations among the joint angles to stabilize the end effector: the covariation among the DOF that does not interfere with the end movement goal (Vucm) and the variability among DOF that does change the movement goal (Vort) (Scholz et al., 2001; Scholz & Schöner, 1999). It is important to note the increases in the Vucm have been used in previous studies to indicate a flexible control strategy. Vucm is the variability that does not change the end effector, so a higher value indicates higher flexibility. However, changes in Vort indicate motor variability that interferes with the task. Examining both of these variables can provide insight into the overall movement strategy. Higher flexibility can be indicated by increased Vucm, while the Vort can decrease or remain unchanged. For example, a flexible control strategy was displayed in a whole-body pointing task. The Vort remained unchanged across tasks (Kim et al., 2012). The higher Vucm has also been observed when balancing a ball or pointing a laser to a small target while standing without a substantial change in the Vort as the task difficulty was increased (Hsu & Scholz, 2012). The adoption of a less flexible strategy is indicated by a decrease in Vucm and an increase in Vort. For example, when posture is challenged, Vucm is reduced, and Vort is increased when standing on a narrow surface when studying older adults compared to a young control group (Hsu et al., 2014). In general, the UCM is a promising method to discriminate control strategy (Rosenblatt et al., 2014). The overall strength of the control strategy can be assessed by comparing Vucm to Vort, also known as the coordination metric (DVz) (Krishnan et al., 2011). Without a high DVz (or Vucm>Vort), the DOF are not coordinated into a control strategy during the task. The magnitude of DVz provides insight into the strength of the control strategy used to stabilize the end effectors (Rosenblatt et al., 2014; Zhang et al., 2008). For a flexible control strategy, since a high Vucm and small Vort are expected, a high DVz would be observed. In a less flexible control strategy, expecting small Vucm and high Vort can induce small DVz.

In addition to the UCM, traditional measures of postural (Hsu et al., 2007, Hsu, Scholz, Schöner and Kiemel, 2007) and manual stability (Gera et al., 2010) can also be used to provide insight into an adopted control strategy and were assessed here. In a postural manual task, because the controller aims to stabilize the body CoM within the base of support and the object within an opening, the variability of body CoM, as well as hand, can be assumed as vital for control strategy analysis. The variation of end effectors occurs as a result of coordinating joints. Therefore, using end effector variability analysis established an understanding of how variability among joint angles is directed on the variability of end effectors (Scholz et al., 2001; Hsu, Scholz, Schöner and Kiemel, 2007). For example, the variability of end effectors has some relation with the Vort. The high variation of body CoM was correlated to the high Vort in quiet standing over a narrow surface with closed eyes (Krishnamoorthy & Kiemel 2005).

The purpose of the *first* study is to explore which control strategy was utilized when postural and manual constraints were systematically manipulated during a postural manual task. We investigated the control strategies that emerged as the postural (size of the support surface: narrow or wide) and manual (precision: small or large opening) challenges of the task were manipulated. In our standing manual task, participants transported a block to an opening (i.e., transport phase) and held it in the opening for 5 seconds (i.e., hold phase). Because both postural and manual constraints were incorporated into our experiment, we examined two end effectors (CoM and hand position) in the UCM and variability analyses.

In this regard, changes in control strategies may depend on which task is prioritized. Specifically, a less flexible control strategy may suggest that the postural task is prioritized (e.g., standing on the narrow surface). In contrast, a flexible control strategy may signify manual prioritization. When there is a falling consequence for the postural manual task, there may be a priority for the safe balance control, and therefore exhibiting postural priority. Rather, when there is only precision demand for the manual task without falling consequence, the posture may facilitate the manual control, or in other words, there may be a manual task priority. In the *second* study, we will address the relationship between task prioritization and postural manual task performance.

To date, most dual-task posture studies have focused on examining changes in postural control. While both postural and manual tasks are well-learned over the human life span, both have consequences if poorly executed, including loss of balance or dropping a valuable object. Consequences may drive prioritization in a manner where the task with the least consequences of failure exhibits the most significant decline in performance. In the *second* study, we examine how both a postural and manual task is prioritized when each has a salient metric of performance (and failure) to the participant. Investigating task priority can provide a better understanding of how the nervous system strikes a balance between safety and mobility (Yogev-Seligmann et al., 2012).

Much of what we know about performing a postural and concurrent task comes from studies where individuals perform a postural-cognitive (Yogev-Seligmann et al., 2008) or gait-manual (Plummer-D'Amato et al. 2012) task. The interference between postural control in standing or walking with the secondary task suggested that task consequences significantly affect performance (Nordin et al., 2010). Competition of resources between tasks can result in a decline in performance, especially in the cognitive task (Doumas et al., 2008), which may be due to the consequences of failure. Specifically, cognitive task failure in the typical paradigm may have fewer consequences than losing one's balance. Dual-task cost (DTC) is often calculated to quantify task priority (Raffegeau et al., 2018). The higher the cost of one task, reflected in a decrease in performance relative to a baseline trial, suggests the task has less priority (Doumas, Smolders, & Krampe, 2008). Likewise, when the manual task was challenged in a walking manual task, one study found the DTC for step length and velocity increased when performing a more complex manual task (carrying pitchers with water on a tray). The higher manual task challenge lowered gait performance (Abbruzzese et al., 2014). Similar findings were observed in other carrying tasks requiring precision (Asai et al., 2014; Nordin et al., 2010). On the other hand, when gait is more complex and potentially more hazardous in regard to task failure, such as climbing stairs, manual task performance declined (Madehkhaksar & Egges, 2016), possibly due to prioritizing posture and balance over the secondary task. Prioritizing posture over other tasks is widely found in the literature and is often referred to as a posture-first strategy (Bloem et al., 2001; Woollacott & Shumway-Cook 2002).

When applied to a postural manual task, like in a standing and fitting task, the association between task consequences, performance, and prioritization has not been examined. It is possible that the findings from a standing postural task will not be equivalent to previous literature examining dual-task walking, given the dynamics of gait are very different compared to static stance. Specifically, gait is inherently less stable than standing given periods of single support and times when the body center of mass is outside of the base of support. A manual task may therefore be less prioritized during gait. In essence, the posture first strategy may not be observed in a dual-task static standing behavior.

In the *second* study, we aimed to investigate how changes in the difficulty of the postural or/and manual task determines the priority of either task. We used the same postural and manual challenges as the first study. Like the past work, we expect prioritization to change as task challenges increase (Raffegeau et al., 2018; Simon-Kuhn et al., 2019). In previous studies, changes in movement variability were used to quantify the cost to show the cost of standing during a postural cognitive task (Doumas, Rapp, & Krampe, 2009). Given the evidence of changes in the variability as a proxy of performance in dual tasks (Huxhold et al., 2006; Doumas et al., 2009; Boisgontier et al., 2013), the variability of the end effectors was used in this study. We had combination of standing on narrow/wide surface and fitting a block to a large/small opening. We assessed dual-task cost (DTC) for variability in the small/narrow, small/wide and large/narrow conditions for hand and CoP. We obtained the DTC by comparing the condition with either postural or manual challenge, and the condition with a combination of both challenges to the condition without any challenge. We used the wide/large condition as a baseline for the DTC calculations for two end-effectors: hand and CoP.

Taken together, the purpose of this study was to explore the emerging control strategies, and task prioritization as the constraints of a postural-manual task were altered. The participants transported and then held a block with an opening for five seconds. We specifically manipulated both postural (support surface size: Narrow or Wide) and manual (opening size: Large or Small) demands of the task.

CHAPTER 2. REVIEW OF LITERATURE

Standing postural control and arm movements are mechanically linked during whole-body reaching tasks, and therefore, the control strategy will combine both tasks in a coordinated pattern of movement. In this dissertation, manipulating the demand of the fitting task or standing on an unstable support surface is expected to change the control strategy, and task priority in a whole-body fitting task.

For the first two sections of this literature review, we reviewed previous studies about coordination, control strategies, and the effect of postural manual constraints. In the last section, we reviewed the studies about the task prioritization.

2.1 Redundancy, coordination and the control strategies

Humans perform multiple voluntary tasks during daily life activity. For example, people transport the body to the desired locations while maintaining upright standing. These movements, such as grasping, reaching, or handling an object are complex since there are more elements involved in the performance than the elements to do these motor tasks. For example, the body has more joints and muscles than needed to configure the hand position or the body center of mass in a standing manual task. This phenomenon, i.e. kinematic motor redundancy, is recognized as a central focus for the organization of the control strategy for the hierarchical control of voluntary movement (Bernstein, 1967).

Bernstein noticed the redundancy in the motor system during a hammering task. He observed smaller variability of the trajectory of the tip of the hammer than the variability of the the endpoint across a series of strikes. This observation suggested to him that the joint angles were changing, such as a kinematic chain correcting each other errors, to stabilize the tip of the hammer configuration. Therefore, there is a flexible family of solutions for joint angles to ensure an accurate and less variable ending point of the hammer (Bernstein, 1967).

A combination of joint angles can co-vary flexibly to enable the motor system to stabilize the end-effector configuration called "synergy," and therefore, achieve the goal of the task (Latash, Scholz, & Schoner, 2007; Yang, Scholz, & Latash, 2007). This flexible coordination of joint angles exists to control posture and head orientation (Park, Schöner, & Scholz, 2012), to control posture when standing on a narrow base of support (Hsu, Lin, Yang, & Cheng, 2014), to control balance with the absence of vision (Hsu, Scholz, Schöner, Jeka, & Kiemel, 2007; Krishnamoorthy, Yang, & Scholz, 2005), and to control posture when performing multiple manual tasks (Hsu & Scholz, 2012). This flexible form of the control strategy is desired but may not be the sole control strategy under different constraints.

A less flexible control strategy can be an alternative that the motor system eliminates some DOF via constraining the variation of joint angles. This less flexible control strategy invokes in an attempt to minimize unnecessary destabilizing movements. For example, by standing on elevated heights that threaten the balance, the mean position of the CoP is shifted backward (Carpenter, Frank, & Silcher, 1999). If an expected consequence during standing is present (e.g., fear of falling), the variability of the CoP displacements increases. If there is no expected consequence (e.g., no possibility of falling), the variability will decrease (Davis, Campbell, Adkin, & Carpenter, 2009). The less flexible strategy is a consequence of the intense contraction of muscles around the joints and typically is a strategy used by people with neurological disorders such as Parkinson patients (Pasman, Murnaghan, Bloem, & Carpenter, 2011).

The less flexible strategy assumes that it is easier for the motor system to control fewer joint angles. With less flexible strategies the DOF shrinks the solution sub-space within the full space of all possible mechanical solutions for the task (Latash et al., 2007). This strategy is not flexible enough to adapt as the constraint of the task changes. Therefore, a more difficult constraint task is reflected as a higher variation in the end-effector configuration, which results in lower accuracy and performance of the task (Scholz & Schöner, 1999). Adopting a stiff posture hinders the ability to change the joint configuration, decreases the optimization of the task performance and limits the ability to attenuate perturbations to balance.

Analogous observations, either flexible or less flexible control strategy, can happen when people are performing the postural manual task in challenging situations.

2.2 Postural and manual constraints and the control strategies

Upright standing is a typical posture that humans perform while performing other tasks (such as reaching) to interact with the environment. Successful performance of posture and manual tasks requires the coordinated action of many components such as joint angles. How these many DOF are organized in such a manner is essential given the high risk of falling and failure in the accomplishment of reaching the task's goals. More critical, redundant joint angles shared between posture and concurrent manual movements have dual roles in preserving balance and unifying to control reaching (Kaminski, 2007). These joint angles are mechanically linked and integrated to form functional synergies, but to some extent, are independent to satisfy the goals of both postural and reaching tasks. This integration between posture and manual degrees of freedom can be modified under postural and manual constraints.

In the presence of only manual constraints with varying difficulty, while standing on a stable support surface, this integration between posture and manual control was examined.. Postural stability has been observed to facilitate manual task with high precision demands. For example, posture was tightly controlled when fitting the block to the small opening (Haddad, Ryu, Seaman, & Ponto, 2010; Haddad, Van Emmerik, Wheat, & Hamill, 2008), pointing to the smaller size target (Berrigan, Simoneau, Martin, & Teasdale, 2006), transporting an object to higher elevation (Huntley, Zettel, & Vallis, 2016), reaching an object at lower height (Huang & Brown, 2013), and reaching to the farther distances (Stapley, Pozzo, Cheron, & Grishin, 1999). The postural changes have indicated that subjects were regulating posture in a manner to provide a controlled posture to assist arm movement (Berrigan et al., 2006).

Additional to the tight postural control, standing on a stable surface allows a backward shift of the body CoP when reaching the far distances. Reaching beyond the arm length is a high precision demanding task requires a backward shift of body CoP to preserve the body CoM within the boundaries of the base of support (Pozzo et al., 2002). This strategy accomplished by trunk, upper and lower body synergies coupled as a functional unit to move the body (Kaminski, 2007).

Empirical evidence has also suggested that stable standing allows flexible control strategy to coordinate redundant DOF. For example, in a whole-body pointing task with a stick to targets of increasing size, the variability within the UCM (Vucm) and the index of synergy (DVz) increased. Therefore, a less flexible synergy was adopted when pointing to the smaller target with greater difficulty and more flexible synergy to accomplish the goal of pointing to the larger target (Kim et al., 2012). Similar behavior was also observed in postural manual task with immobilized body joints. The restriction in the joint angles decreased the Vucm to stabilize body CoM with higher difficulty in the control of posture (Hsu, 2014). During multiple manual tasks, flexible control was also observed when pointing to the target and ball balancing (Hsu & Scholz, 2012).

In the presence of postural threats, the integration between postural and manual control reveals complex behavior. The motor system has to solve two different problems and, therefore, the motor system needs to coordinate all redundant degrees of freedom for performing two separate tasks unified into one task. The coordination to satisfy this dual role is complex given the linked kinematic behavior of maintaining the body CoM within the base of support and the control of reaching. In particular, it was postulated that the preservation of posture is the primary goal during reaching tasks. For example, while reaching for an object, participants lean less towards an object when standing on the foam than when standing on the stable surface (Voudouris, Radhakrishnan, Hatzitaki, & Brenner, 2013). Paizis et al., (2008) also observed when participants performed whole-body reaching on a narrow support surface, posture was preserved while the wrist kinematics were modified. The anterior-posterior displacement of the CoM also decreased, and a straighter wrist trajectory was produced (Paizis, Papaxanthis, Berret, & Pozzo, 2008). Hilt et al., (2016) also observed smaller backward hip displacement during a whole-body pointing task on a narrow surface to limit the anterior-posterior displacement of CoM. This strategy was balance-efficient rather than beneficial to reaching (Hilt et al., 2016).

In a few studies, the flexibility of the control strategy over a narrow support surface has been investigated. For example, the Vucm and the flexibility of the control strategy were increased when standing up (Reisman, Scholz, & Schöner, 2002), when standing up with keeping light finger touch (Scholz, Reisman, & Schoner, 2001), and when quietly standing (Krishnamoorthy et al., 2005). A concurrent postural manual precision task has the advantage of recruiting whole body

DOF for balance and manual tasks. The complexity of the control strategy also increases when standing on a narrow surface and performing a precision demanding manual task.

2.3 Task prioritization in postural and manual tasks

Task prioritization arises due to shared sensory, motor, and central resources. In the competition between two motor tasks, the central nervous system gives priority to the task with higher demands (Huxhold, Li, Schmiedek, & Lindenberger, 2006; Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997). While one task demand increases, the performance of the concurrent task becomes impaired (Kerr, Condon, & McDonald, 1985; Shumway-Cook et al., 1997).

Previous studies demonstrated postural task priority in destabilizing situations and cognitive task priority when standing over a stable surface. Postural task priority was observed when standing on an elevated height (Adkin, Frank, Carpenter, & Peysar, 2000), on a sway-referencing surface (Doumas et al., 2008), on an unstable surface (Dault, Geurts, Mulder, & Duysens, 2001), and while standing on a perturbing platform (Müller, Redfern, & Jennings, 2007). Cognitive task priority was observed when standing on a solid surface and when completing a sentence (Woollacott & Shumway-Cook, 2002), performing a memory task (Huxhold et al., 2006), or mental arithmetic (Lee, Goyal, & Aruin, 2018). In the postural manual tasks, there is a shared set of joint angles with a mutual association on the whole-body control. This association mandates a priority when both tasks have some consequences. For example, failure in the postural manual task may consequence in falling, and dropping the object may happen because of deficient manual control.

Some studies have demonstrated the effect of task prioritization on the control strategy behavior. Solnik et al. (2013) showed for less prioritized tasks with the highest level of manual constraint, the control strategy had higher flexibility reflected in higher Vucm and Vort without any change in the synergy index (Solnik et al., 2013). In their study, some exploratory behavior was allowed to select the best solutions when pointing with less comfortable positions. The control strategy may take less flexible behavior when postural control is prioritized. The flexibility of the control strategy will allow the motor system to converge to coordinated joints that accomplishes the precision demands of the prioritized task.

2.4 Concluding remarks

In this chapter, we reviewed literature from different perspective connecting to the purposes of our study. Given different findings in the reviewed studies, the motivation for this study is to understand how the motor system modulates and prepare for the control strategy and the priority for performing precision demanding manual and postural tasks in a threatening standing scenario. Thus far, research on postural or manual task performance has focused on the co-variation of joint angles to stabilize the arm or the center of body mass as indicators of coordination between joint angles. In the current study, kinematic indicators and the coordination between changes in the joint angles will be considered.

CHAPTER 3. METHODS AND PROCEDURE

3.1 Participants

For the first study, a group of 12 young, healthy individuals was recruited. For the second study, we had 23 young healthy participants (20-35 years). Any participant with a history of orthopedic or neurological disorders was excluded.

3.2 Apparatus

In all trials, participants stood on an AMTI force platform. Body and hand movements were recorded using a VICON motion capture system. MotionMonitor software synchronized the data from the force platform and the motion capture system. Participants were instrumented with small retro-reflective markers with adjustable Velcro wraps. These reflective markers were placed on the hand, forearm, upper arm, upper back, waist, tights, calves, and feet. Subjects were asked to wear tight-fitting athletic clothing to minimize movement from the markers. We identified three-dimensional joint angles, hand marker coordinates, body CoM, and CoP using MotionMonitor software. Joint angles were calculated in three dimensions using the Grood and Suntay (1983) method. CoM was estimated by MotionMonitor using the Winter method (Winter, 2009). All data was collected at 250Hz.

3.3 Procedure

Upon arrival at the biomechanics laboratory, the procedures were explained to the participant, and informed consent was obtained. Arm length, foot length, height, weight, age, gender, and hand dominance were recorded. The participant then was instrumented with reflective markers.

Participants stood on the support surface and kept their feet shoulder-width apart. Foot position was marked on the support surface to maintain the same foot orientation during the entire testing time. The support surface was located approximately 5cm off the ground (Figure 1).

Participants were required to fit a block (81 cm^2, 50 g) through a square opening that is cut into a fitting board. The fitting board was placed at a distance equivalent to 4/3rd of the participant's arm length. The opening in the fitting board was at shoulder height. An LED light was affixed to the fitting board and illuminated if the block hits the perimeter of the opening. This feedback provided the participant with information about their fitting accuracy. A video camera was placed behind the participant during data collection. The height and the distance of the fitting board and the height of the block's table were adjusted for each participant.

In all trials, participants were instructed to pick up a block that was located on a table at the wrist height and fit it as accurately as possible into either the large or small opening. The fitting board opening was either small (121 cm^2) or large (196 cm^2) while the support surface was either narrow (1/3rd of foot length) or wide. There was, four unique conditions, a combination of opening size/support surface size: Large/Narrow, Large/Wide, Small/Narrow, and Small/Wide.

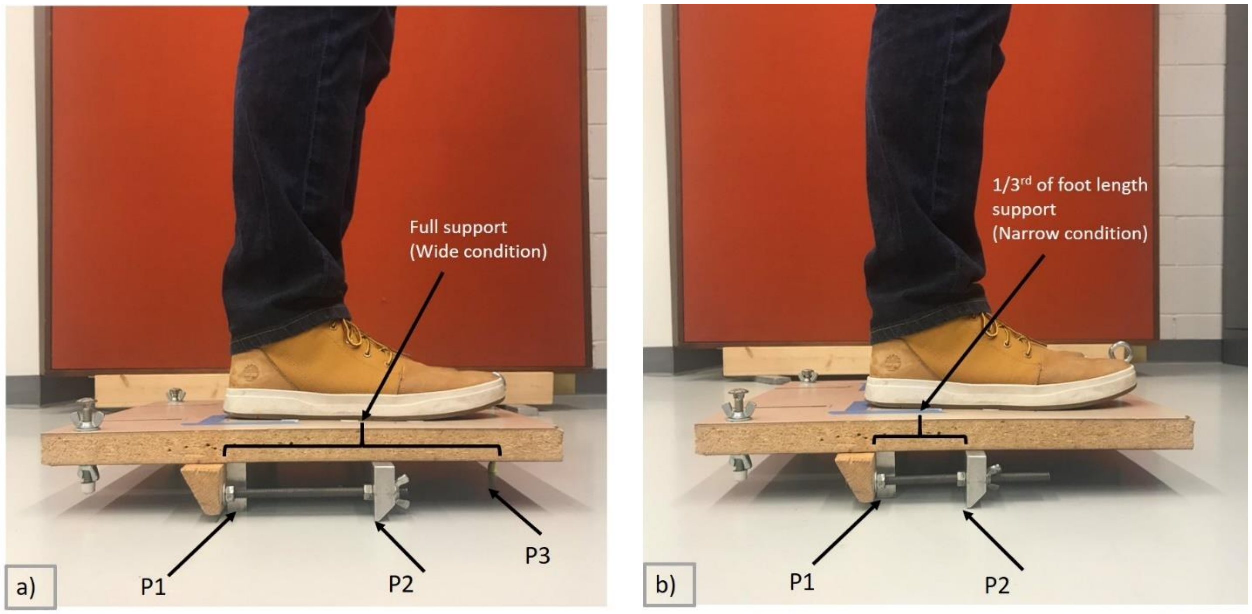

Figure 1. Support surface when a) standing on the wide surface with three points of contacts with the ground and b) standing on the narrow surface with two-point of contacts with the ground

During each trial, the experimenter cued the participant to begin. Participants then grasped the block from the table with their dominant hand and transported it to the opening (transport phase). The block was then held within the opening (hold phase) until the experimenter cued the participant to return the block to the table (Return phase). This return cue was given to the participant approximately 5 seconds after the block first broke the plane of the opening (Figure 2). It was emphasized to the participant that the block should be placed within the opening as accurately as possible, and the support surface should remain as flat as possible. Participants performed three familiarization trials at the start of the experiment.

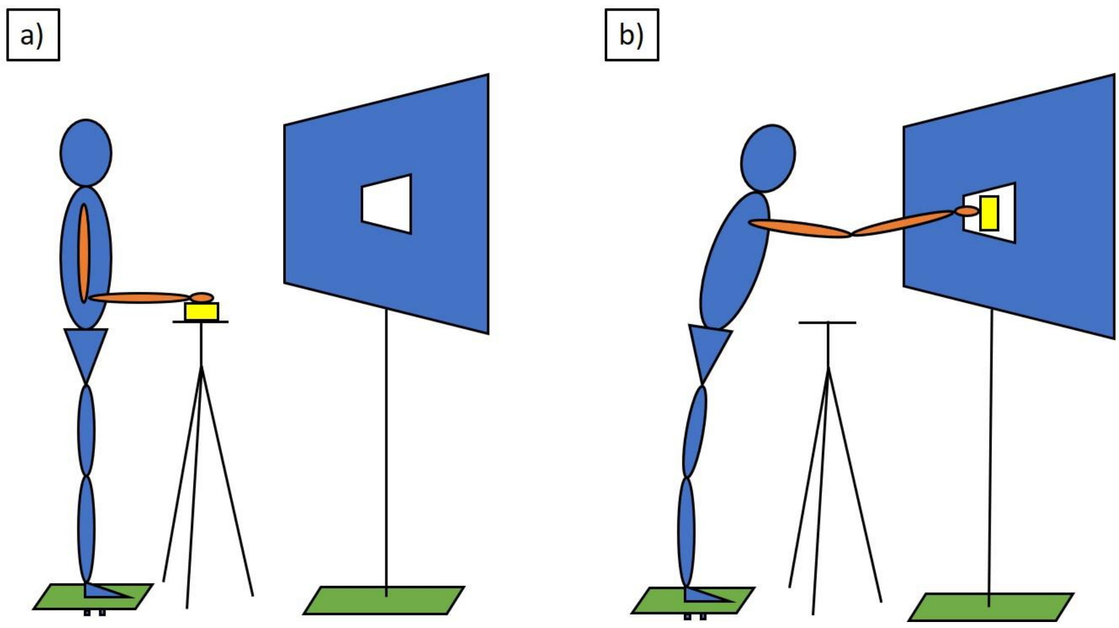

Figure 2. During the fitting procedure, participants a) picked up a block and b) fitted the block into the opening while standing on the support surface.

If the block contacts the perimeter of the opening, that trial was coded with a hit error. A trial with a surface error was coded if the support surface wobbles (deviates from being flat). When an error occurred, the participant was asked to continue with the trial and readjust the block and/or the standing surface.

Participants performed 40 repetitions per trial for a total of 160 trials. The support surface manipulations were blocked, and the opening size manipulations were randomized within each block. Half of the participants started with the narrow size trials and the other half with the wide size ones. Participants had approximately 3-5 minutes rest-break between every 40 trials. The testing session lasted approximately 90 minutes.

3.4 Data Analysis

3.4.1 Error measurements

We code both hit and surface errors. Only trials where no errors were made was used in the analysis. We selected only successful trials to become sure the motor behavior of participants was consistent across trials. Inclusion of trials with errors would make an inconsistent behavior of participants and therefore we would be unable to conduct variability analysis across trials.

Hit errors were coded by watching the synchronized video. Any trial where the LED illuminated was coded as a trial with hit error.

A kinematic method was used for detecting trials with surface errors. A surface error was defined as the vertical displacement of the foot marker at any time-normalized percent, deviated below 3*standard deviation of the mean vertical foot position during the standing on the wide support surface and fitting to the large opening condition (Figure 3).

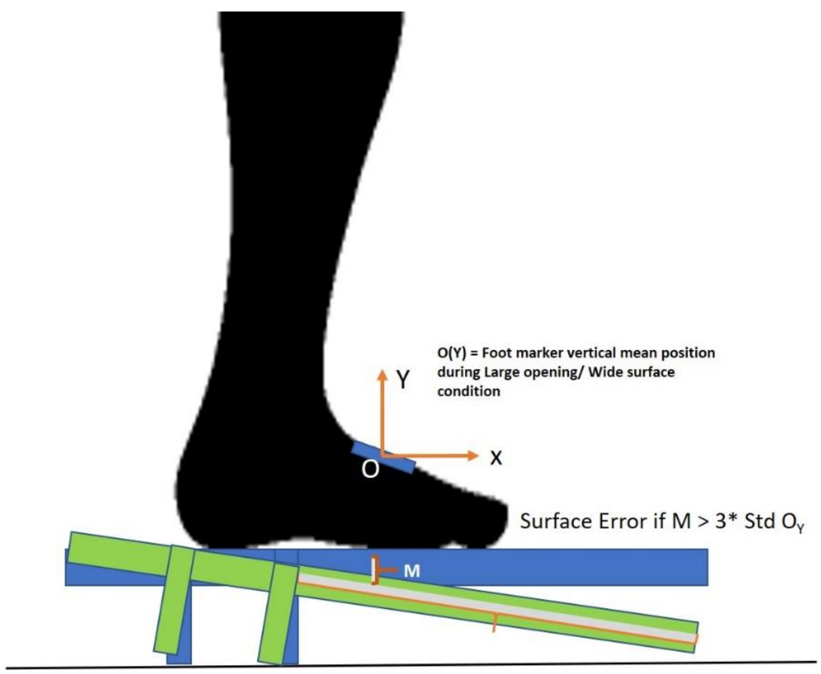

Figure 3. Kinematic method for detecting surface errors.

3.4.2 Separation of three phases and preparation of the data

We randomly selected 20 successful trials with no errors. The hand marker position, body CoM, CoP, and joint angles were used to calculate the dependent variables. All data were filtered with a zero-lag, 4th order, low pass Butterworth filter using a 12 Hz cut off frequency. All data of the selected trials were processed and analyzed using Matlab 2018a.

Each trial was divided into transport, hold and return phases. The hand marker anterior-posterior (AP) speed profile (calculated using the first central difference method) was used to determine the phases of the trial. Five percent of the maximum hand speed was used to indicate the start and end of each phase (Figure 4).

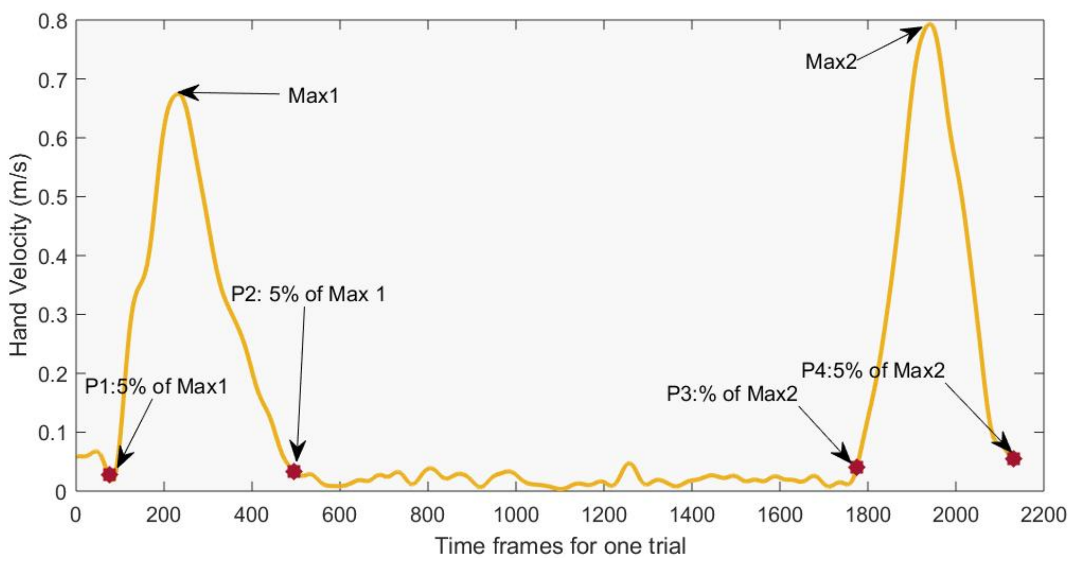

Figure 4. An example of the hand speed profile depicting how the fitting, transport, hold and return phases of the movement were determined.

3.4.3 Data analysis for the control strategies - the first study

To address the purposes of the first study, we only examined the hold phase of the trials.

Hold Phase

We calculated the CoM average standard deviation (CoMSD), and hand position average standard deviation (handSD) across trials.

We also used the Uncontrolled Manifold hypothesis (UCM) (Latash, Scholz, & Schoner, 2002; Scholz, Schöner, & Latash, 2000). We specifically evaluated the co-variation among all available DOF (Joint configurations) to stabilize the end-effectors (body CoM and hand positions).

The 13 joint angles for the UCM analysis were: Ankle (Flexion, Rotation), Knee Flexion, Hip (Flexion, Abduction, Rotation), Shoulder (Flexion, Abduction, Rotation), Elbow Flexion, Wrist (Flexion, Abduction, Rotation). The UCM space had 10 dimensions (13-3 = 10) for either hand position or CoM. The flexibility in performance was allowed by variation within this subspace. The orthogonal subspace to the UCM space had 3 dimensions for hand position and CoM. Variations in joint angle configuration within the orthogonal subspace lead to changes in the CoM or hand position. We partitioned the variability of joint configuration across repeated trials into two components. The UCM component represented fluctuations of the joint configuration that does not affect the value of the end-effector, called "UCM Variability (Vucm)." The second component represented changes in the joint configuration that change the end-effector configuration, "Orthogonal Variability (Vort)" (Park et al., 2012). We conducted the UCM analysis separately for the CoM and the hand position as end effectors. Details of the UCM analysis are as follow:

1) All joint angles data and the body CoM and hand position were normalized to 100 percent using a cubic spline interpolation.

2) We obtained the Jacobian matrix to model the relationship between changes of the end-effector position to the joint angle configuration. We obtained the Jacobian matrix by calculating coefficients of the multiple linear regression relating mean-free joint angles to the mean-free end-effector position for each percent. The Jacobian matrix described how small changes in the joint angles affect the end-effector position (Ferreira de Freitas & Scholz, 2010).

3) The null space of the Jacobian or the subspace in joint angle space whose position does not affect the end-effector position was obtained.

4) The difference between current and average configuration was projected into the null space (UCM subspace) and the orthogonal space at each time-normalized sample.

5) At each time-normalized point, the variances across trials were computed for both UCM and orthogonal spaces. We squared these projected lengths and summed the averages across trials of one condition to reach variance components.

6) The UCM variance was normalized to the dimension of the UCM subspace (UCM DOF = 10) and the orthogonal variance divided by the dimension of the orthogonal subspace (ORT DOF = 3) to reach Vucm and Vort per degrees of freedom. We averaged Vucm and Vort components across trials at each point of time-normalized of each unique condition yielding one Vucm and Vort. We log-transformed both Vucm and Vort prior to statistical analysis (Verrel, 2010). We separately calculated Vucm and Vort per degree of freedom for both end-effector, including CoM (CoMVucm and CoMVort) and hand position (Hand Vucm, Hand Vort).

7) We finally calculated DVz (the index of coordination) for control of both body COM and hand movements (CoM DVz and Hand DVz). The DVz coordination metric was used to quantify task-specific co-variation in the joint angles that separately stabilized each set of task variables (COM and hand position). The relative amount of Vucm in the total variance was computed as a coordination metric (Equation. 1), which normalized by a Fisher Z-transformation (Equation.2).

Equation. 1 $$DV = ((Vucm/ (n - d)) - (Vort/d))/(Vtot/n)$$

Equation. 2 $$DVz = 0.5 * log(((n/d) + DV)/((n/(n-d)) - DV))$$

As shown in the Equation 1 and 2, *n* is the dimension of the full space (n = 13), *d* is the dimension of the orthogonal space (d = 3), and Vtot is total variance equal to the sum of Vucm and Vort. DVz is the Z-transformed DV to express coordination metric as a Z-Score because both Vucm and Vort are non-negative numbers and, therefore, DV has a deviation from a normal distribution and is a bounded measure between (-n/d) and (n/(n-d)).

3.4.4 Data analysis for task priority– the second study

We used the variability (Ellipse Area) for the Dual-task cost (DTC) calculations. We calculated DTC as (DTC = [(Task - baseline)/baseline] *100) for the two end-effectors (hand and CoP). We used the standing on the wide surface and fitting to the large opening as the baseline condition for all DTC calculations. DTC expresses the effects of additional task costs imposed in the conditions with task challenges to the baseline task with no challenge. Our dependent variables were DTC for CoP (CoP Var DTC), hand (hand Var DTC).

We also used the number of trials with task errors (Surface Error and Hit Error) to test the change in task accuracy.

For our analyses, we used Matlab software (MATLAB 2018a. Natick, Massachusetts: The MathWorks Inc).

3.5 Statistical analysis

For the first study, we conducted a two-way repeated measure ANOVA (support surface and opening size as within-subject factors) to compare changes of postural and hand DVz, Vucm, Vort, and SD under different postural and manual difficulties.

For the second study, we used a two-tailed t-test to determine if DTCs and the number of task errors were different from zero (i.e., the baseline value). We also conducted a paired t-test between hand and postural DTCs (hand Var DTC versus CoP Var DTC) to determine the priority of either postural or manual tasks.

Significance was assessed at $\alpha = 0.05$.

CHAPTER 4. MANUSCRIPT 1: TASK-SPECIFICIFIC CONTROL STRATEGIES WHEN PERFORMING A POSTURAL MANUAL TASK

4.1 Abstract

The concurrent control of both standing and manual tasks are sophisticated since redundant, mechanically linked degrees of freedom (DOF) must be coordinated by a control strategy in a manner that affords completion of both tasks (Berret, Chiovetto, Nori, & Pozzo, 2011). In previous studies, a flexible control strategy was typically adopted and presented as the best behavior in the young adults in a task with only a manual task challenge (Kim et al., 2012) or postural task demand (Reisman et al., 2002). We argued the flexible control strategy is the byproduct of experimental design with minimal challenge. When both manual and postural tasks are challenging, the motor system may adopt a less flexible control strategy to coordinate joint angles. We aimed to show that a less flexible control strategy can adapt to the challenges of a postural manual task in young adults.

Twelve healthy participants (25 ± 4.2 years) performed a fitting task that required a small block to be transported, fitted, and held in a small or large opening for five seconds while standing on a narrow or wide surface. In addition to the uncontrolled manifold (UCM) analysis (variability spanned in the UCM space (Vucm), orthogonal space (Vort), and coordination metric (DVz) for hand and CoM control, we determined the hand and CoM standard deviation (SD) on 20 error-free trials (no block contact with the opening and no tilting of the surface). We found higher CoM and hand SD as well as invariant CoM and hand Vucm imposed by the narrow surface, which resulted in a reduction of joint-angle variability (less flexible control strategy) while holding a block in the small or large opening. The smaller CoM and hand SD, and greater Vucm, suggested a more flexible control strategy was adopted when standing on a wide surface and attempting the action of fitting the block to the small opening. The strength of the control strategy remained high across

these conditions (high DVz). We concluded that a flexible control strategy is not a ubiquitous movement strategy in young adults (at both levels of coordinating joint angles and the variability of end effectors). We argued that the postural constraint (i.e., standing on the narrow surface) is the driving factor in the control strategy throughout a postural manual task. The immobilization of joints and muscle co-contraction were discussed that facilitated the postural task priority. The consequence of postural constraint (i.e., falling) appeared to increase the notion of postural control and explained our findings.

4.2 Introduction

Performing complex movement requires redundant and mechanically linked DOF to be coordinated in a manner that allows the goals of a task to be accomplished (Hilt, Berret, Papaxanthis, Stapley, & Pozzo, 2016; Morasso et al., 2010; Pozzo, Stapley, & Papaxanthis, 2002).

The nervous system can utilize various control strategies when performing these complex movements. In studies with a single task constraint, a flexible control strategy is often considered to be optimal and frequently observed in younger adults. In contrast, a less flexible control strategy is often observed in older adults (Hsu et al., 2014) or in people with motor disorders (Falaki et al., 2016). A control strategy is considered flexible when there is a high variation among DOF, which are utilized adaptively to ensure task performance (Goodman et al., 2005). In a flexible control strategy, the high covariation among DOF is used to compensate for movement errors that occur at the level of the individual DOF (Freitas et al., 2010). This strategy inevitably creates a variety of possible trajectories by the joints to complete the task and is, therefore, considered a more adaptive strategy.

Consequently, a less flexible strategy is when DOF covariation is constrained, resulting in stiffness and a reduction in individual joint flexibility (Latash et al., 2007). Technically, a less flexible control strategy has the advantage of utilizing specific mathematical solutions to the problem of kinematic redundancy; therefore, this may exploit just enough variability among DOF to achieve stable control of the end effectors (Bernstein, 1967; Hsu et al., 2014; Latash et al., 2007). In a less flexible control strategy, movements of the body are easier to control but less adaptable since possibilities for movement are reduced, resulting in a reduced ability to attenuate perturbations or perform in a dynamic environment.

Typically, in young adults performing an easy task with a minimal challenge (e.g., a task with minimal constraints), a flexible control strategy would be observable. For example, when performing a relatively easy task (pointing) while standing on a stable surface, young adults exhibit high flexibility (Solnik et al., 2013). Young adults also appear to exhibit high flexibility when performing manual tasks with single task constraints (e.g., a manual only or standing only task), even as the constraints become more difficult. For example, if a young adult performs a task with manual constraints such as pointing a laser and balancing a ball on a tray (Hsu & Scholz, 2012), or standing on a narrow surface continuously for 20 seconds, young adults adopt a flexible control strategy (Hsu et al., 2014).

However, the idea that a more flexible control strategy is ubiquitous and always observed in young adults is not always the case. Rather, the specific strategy utilized depends to a large extent on the task constraints, as well as the consequences of failure (e.g., falling). In difficult tasks with dual constraints (e.g., adopting a difficult posture while reaching for an object), allowing a flexible control strategy with extraneous and variable movements among DOF (e.g., joint angles) may result in task failure. In such a case, adopting a freezing strategy may be more optimal since variable movements may be more difficult to control. Additionally, consequences associated with task failure may cause the utilization of a less flexible strategy. In such a case, a less flexible control strategy, although less adaptable, may be more controllable and minimize the chance of producing a self-generated perturbation. How the nervous system adopts control strategies when performing a posture and manual task with varying constraints has not been examined. Studying such control strategies is essential since many common tasks are performed while standing, and task failure can result in a fall.

Movement control strategies have primarily been investigated using the UCM analysis (Latash et al., 2002; Scholz & Schöner, 1999). The UCM examines the structure of variability among DOF (Freitas et al., 2010; Latash et al., 2002; Scholz & Schöner, 1999; Scholz et al., 2000). Based on the UCM hypothesis, the controller coordinates the joints by the use of two types of covariations among the joint angles to stabilize the end effector: the covariation among the DOF that does not interfere with the end movement goal (Vucm) and the variability among DOF that does change the movement goal (Vort) (Scholz et al., 2001; Scholz & Schöner, 1999). It is important to note the increases in the Vucm have been used in previous studies to indicate a flexible control strategy. Vucm is the variability that does not change the end effector, so a higher value indicates higher flexibility. However, changes in Vort indicate motor variability that interferes with the task. Examining both of these variables can provide insight into the overall movement strategy. Higher flexibility can be indicated by increased Vucm, while the Vort can decrease or remain unchanged. For example, a flexible control strategy was displayed in a whole-body pointing task. The Vort remained unchanged across tasks (Kim et al., 2012). The higher Vucm has also been observed when balancing a ball or pointing a laser to a small target while standing without a substantial change in the Vort as the task difficulty was increased (Hsu & Scholz, 2012).

The adoption of a less flexible strategy is indicated by a decrease in Vucm and an increase in Vort. For example, when posture is challenged, Vucm is reduced, and Vort is increased when standing on a narrow surface when studying older adults compared to a young control group (Hsu et al., 2014). In general, the UCM is a promising method to discriminate control strategy (Rosenblatt et al., 2014). The overall strength of the control strategy can be assessed by comparing Vucm to Vort, also known as the coordination metric (DVz) (Krishnan et al., 2011). Without a high DVz (or Vucm>Vort), the DOF are not coordinated into a control strategy during the task. The magnitude of DVz provides insight into the strength of the control strategy used to stabilize the end effectors (Rosenblatt et al., 2014; Zhang et al., 2008). For a flexible control strategy, since a high Vucm and small Vort are expected, a high DVz would be observed. In a less flexible control strategy, expecting small Vucm and high Vort can induce small DVz.

In addition to the UCM, traditional measures of postural (Hsu et al., 2007, Hsu, Scholz, Schöner and Kiemel, 2007) and manual stability (Gera et al., 2010) can also be used to provide insight into an adopted control strategy and were assessed here. In a postural manual task, because the controller aims to stabilize the body CoM within the base of support and the object within an opening, the variability of body CoM, as well as hand, can be assumed as vital for control strategy analysis. The variation of end effectors occurs as a result of coordinating joints. Therefore, using end effector variability analysis established an understanding of how variability among joint angles is directed on the variability of end effectors (Scholz et al., 2001; Hsu, Scholz, Schöner and Kiemel, 2007). For example, the variability of end effectors has some relation with the Vort. The high variation of body CoM was correlated to the high Vort in quiet standing over a narrow surface with closed eyes (Krishnamoorthy & Kiemel 2005).

The purpose of this study was to explore which control strategy was utilized when postural and manual constraints were systematically manipulated during a postural manual task. We investigated the control strategies that emerged as the postural (size of the support surface: narrow or wide) and manual (precision: small or large opening) challenges of the task were manipulated. In our standing manual task, participants transported a block to an opening (i.e., transport phase) and held it in the opening for 5 seconds (i.e., hold phase). The UCM analysis (Vucm, Vort, and DVz), and the end effector variability (SD) were used to assess control strategy in the hold phase. Because both postural and manual constraints were incorporated into our experiment, we examined two end effectors (CoM and hand position) in the UCM and variability analyses.

We hypothesized 1) when both the postural and manual constraints of the task are difficult with dual constraints (narrow surface/small opening condition) a less flexible control strategy will emerge, 2) when there is a minimal challenge with a singular manual task constraint (wide surface/small opening condition) a flexible control strategy will be observed, and 3) when there is a challenge with a single postural constraint (in narrow surface/large opening condition) a flexible control strategy will emerge. The condition without any constraint (wide surface/large opening) served as a control condition to determine relative changes in the flexibility of the control strategy. For hypotheses one through three, we expected that interaction between opening size and support surface size would be observed in our dependent variables, meaning in a condition with both postural and manual constraints, the most significant changes occur compared to the conditions with only a postural or manual task challenge. For the first hypothesis (in a less flexible control strategy), we expected smaller hand and CoM Vucm and DVz and a higher end effector's variability and Vort (during the hold phase). The less flexible control strategy is anticipated because it stiffens posture. For the second and third hypotheses (in the flexible control strategy), we expected greater hand and CoM Vucm and DVz along with smaller Vort and end effectors variability (in the hold phase).

4.3 Methods

4.3.1 Participants

A group of 12 young, healthy individuals (25 ± 4.2 years, seven females and five males) participated in the study. We excluded any participant with a self-reported history of orthopedic or neurological disease.

4.3.2 Apparatus

In all trials, participants stood on an AMTI force platform. Body and hand movements were recorded using a Vicon motion capture system. MotionMonitor software was used to synchronize the motion capture and the force platform data. Participants were instrumented with small retro-reflective markers using adjustable Velcro wraps. These reflective markers were positioned on the hand, upper arm, forearm, upper back, waist, thighs, lower legs, and feet. Participants were asked to wear tight-fitting athletic clothing to minimize marker movement. We identified three-dimensional joint angles, hand marker coordinates, body CoM, and CoP using MotionMonitor software. Joint angles were calculated in three dimensions using the Grood and Suntay (1983) method. CoM was estimated by MotionMonitor using the Winter method (Winter, 2009). All data were collected at 250 Hz.

4.3.3 Procedure

Upon arrival at the biomechanics laboratory, we explained procedures to each participant, and informed consent was obtained. We recorded arm length, foot length, height, weight, age, gender, and hand dominance. Participants were next instrumented with the reflective markers.

Participants stood on the support surface with their feet shoulder-width apart. To ensure the same position was maintained during the entire testing session, the foot position was marked on the support surface. We placed the fitting board at 4/3 of the participant's arm length. The opening in the fitting board was placed at shoulder height.

Participants were instructed to pick up a block (81 cm^2, 50 g) that was located on a wrist-height table in all trials, and then transport and fit the block as accurately as possible into either a small (121 cm^2) or large (196 cm^2) opening, while standing on either the narrow (1/3 of foot length) or wide support surface (250 cm^2). The support surface was located approximately 5 cm off the ground (Figure 1). Therefore, we had four unique conditions: large/narrow, large/wide, small/narrow, and small/wide.

An LED was affixed to the fitting board and illuminated when the block contacted the perimeter of the opening to provide accurate information to the participant. A video camera was placed behind the participant during data collection to capture movement. If the block contacted the perimeter of the opening, that trial was coded as a hit error. A trial was coded as a surface error when the support surface wobbled (deviated from being flat). When these errors occurred, the participant was asked to continue with the trial and readjust the block or the standing surface.

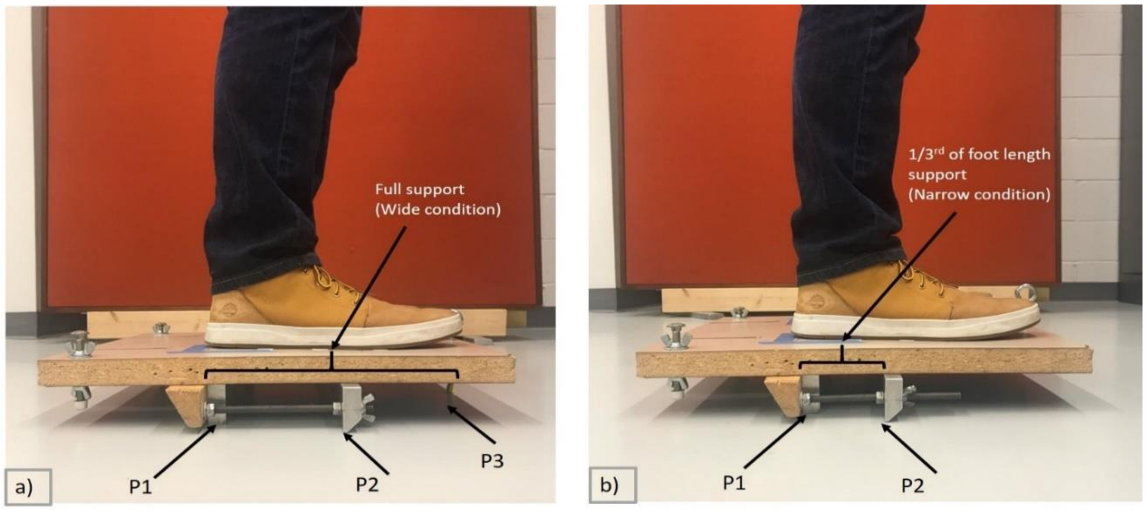

Figure 5. Support surface when a) standing on the wide surface with three points of contact with the ground and b) standing on the narrow surface with two points of contact with the ground.

During each trial, the experimenter cued the participant to begin. Participants then took the block from the table with their dominant hand and transported it to the opening (transport phase). The block was held within the opening (hold phase) until the experimenter cued the participant to return it to the table (return phase). This return cue was given to the participant approximately five seconds after the block crossed the opening (Figure 2). We emphasized to the participant that the block should be placed within the opening as accurately as possible, and the support surface should remain as flat as possible. Participants performed three familiarization trials before the start of experimental trials.

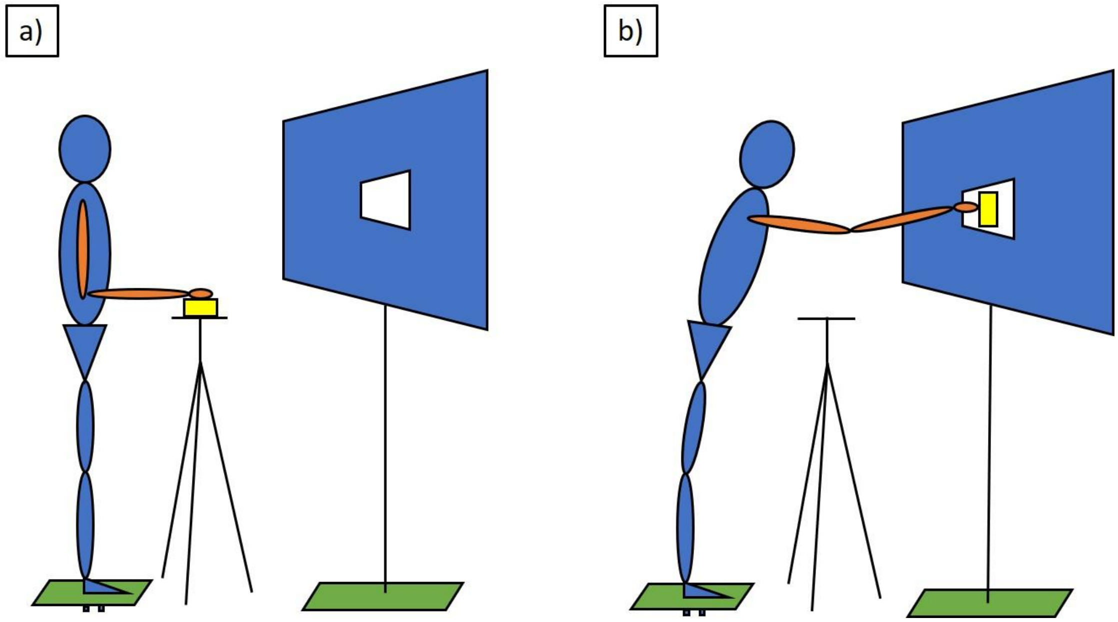

Figure 6. During the fitting procedure, participants a) picked up a block and b) fitted the block into the opening while standing on the support surface.

Participants performed 40 repetitions per trial for a total of 160 trials. The support surface manipulations were blocked, and the opening size manipulations were randomized within each block. Every other participant began with the narrow opening trial and the following participant with the wide opening. Participants had approximately 3–5 minutes rest break between every 40 trials. The testing session lasted roughly 90 minutes.

4.3.4 Data analysis

Error measurements

To ensure consistent behavior across trials, we excluded trials with a hit or surface error. We selected only successful trials to become sure the motor behavior of participants was consistent across trials. Inclusion of trials with errors would have resulted in inconsistent behavior by participants, and therefore, we would have been unable to conduct variability analysis across trials.

Two coders watched the synchronized video to exclude trials with hit errors. Any trial where the LED illuminated, flickered, or flashed was coded as an error. We conducted Cohen's kappa test of agreement between two coders during four conditions and for 40 trials in each condition. There was a strong agreement between the two coders ($p < 0.0005$). The Cohens' kappa agreement between two coders was $k = 0.901$ for large/narrow, $k = 0.960$ for small/narrow, and $k = 0.933$ for small/wide. We only used the first coder records to exclude trials with hit errors.

A kinematic method was used for detecting trials with surface errors. A trial with a surface error was determined when the vertical displacement of the foot marker, at any time-normalized percent, deviated below 3*SD of the mean vertical foot position during the large/wide condition.

Kinematic and UCM analysis

We randomly selected 20 successful trials with no errors. Hand marker position, body CoM, CoP, and joint angles were used to calculate the dependent variables. All data were filtered with a low-pass Butterworth (zero-lag, fourth-order) using a 12-Hz cutoff frequency. All data were analyzed using Matlab 2017a software.

Each trial was divided into a transport, hold, and return phase. The hand marker anterior-posterior (AP) velocity profile (calculated using the first central difference method) was used to separate the phases of the trial. Five percent of the maximum hand velocity was used to indicate the start and end of each phase. To address the hypotheses of this study, we examined only the hold phase (UCM and end effector variability).

Hold phase

We calculated the CoM average SD (CoMSD) and hand position average SD (handSD). We also used the UCM to determine the extent of variance among available joint angles that stabilized the body CoM and hand configuration. The 13 joint angles for the UCM analysis were ankle flexion and rotation; knee flexion; hip flexion, abduction, and rotation; shoulder flexion, abduction, and rotation; elbow flexion; and wrist flexion, abduction, and rotation. The UCM space has 10 dimensions (13–3 = 10) for either hand position or CoM. Variation in UCM space allows for flexibility in performance. The orthogonal space to the UCM space has three dimensions for hand position and CoM. Variations in joint-angle configuration within the orthogonal subspace led to changes in the CoM or hand position.

We partitioned the variability of joint configuration across repeated trials into two components. The first component was called the UCM variability (Vucm) that represents the variation of the joint configuration without any effect, such as changes, on the configuration of the end effector. The second component is called orthogonal variability (Vort), which is contrary to Vucm and represents changes in the end effector configuration (Park et al., 2012). We conducted the UCM analysis separately for the CoM and the hand position as end effectors. Details of the UCM analysis are:

1) All joint-angle data and the body CoM and hand position were normalized to 100% in Matlab, by means of cubic spline interpolation.

2) We used the coefficients of the multiple linear regression (at each 1%) to obtain the Jacobian matrix. These coefficients represent the relationship between the changes of the mean-free end effector position to the mean-free joint-angle configurations (Ferreira de Freitas & Scholz, 2010).

3) Following the second step, we calculated the linear approximation of the UCM space by computing the null space of the Jacobian matrix.

4) The next step was to project the difference between the sample joint configuration at each 1% and the joint configuration mean into the UCM and the orthogonal spaces.

5) We further calculated the variances of the projection lengths across trials at each 1% of the normalized sample for both UCM and orthogonal spaces. We performed this step by calculating the square of projected lengths, and then we summed the averages across trials of one condition to calculate the variance components.

6) The UCM variance was normalized to the dimensions of the UCM subspace (UCM DOF = 10) and the orthogonal variance divided by the dimensions of the orthogonal subspace (ORT DOF = 3) to reach Vucm and Vort per DOF. As the variance components are relatively stable across trials, we averaged Vucm and Vort components across trials at each point of time-normalized by each unique condition yielding one Vucm and Vort. We log-transformed both Vucm and Vort prior to statistical analysis (Verrel, 2010). We separately calculated Vucm and Vort per DOF for CoM (CoMVucm and CoMVort) and hand position (hand Vucm, hand Vort).

7) We finally calculated DVz (the index of coordination) for control of both body CoM and hand movements (CoM DVz and Hand DVz). The DVz coordination metric was used to quantify task-specific covariation in the joint angles that separately stabilized each set of task variables (CoM and hand position). The relative amount of Vucm in the total variance was calculated as a coordination metric (Equation 1), normalized by a Fisher Z-transformation (Equation 2).

Equation 1 $DV = ((Vucm/ (n-d)) - (Vort/d))/(Vtot/n)$

Equation 2 $DVz = 0.5 * log(((n/d) + DV)/((n/(n-d)) - DV))$

In Equations 1 and 2, n is the dimension of the full space (n = 13), d is the dimension of the orthogonal space (d = 3), and Vtot is total variance equal to the sum of Vucm and Vort. DVz is the Z-transformed DV to express the coordination metric as a Z-score because both Vucm and Vort are non-negative numbers and deviate from normality.

4.3.5 Sample size calculation

For the sample size calculation, we used a moderate effect size (= 0.5), with the alpha level = 0.05 and the a priori power = 0.8, with a two-way repeated measure ANOVA (two within factors) test. The calculated sample size using the method recommended by O'Brien and Shieh (1999) in G*Power (version 3.1.9.4) was 12 participants (Faul, Erdfelder, Lang, & Buchner, 2007).

4.3.6 Statistical analysis

We conducted a two-way repeated measure ANOVA with the support surface and opening size as within-subject factors to compare changes of variables under different postural and manual difficulties for all kinematic and coordination metrics. Significance was assessed at $\alpha = 0.05$. All statistical analyses were completed using SPSS software (IBM SPSS Statistics for Windows, version 23.0. Armonk, NY).

4.4 Results

4.4.1 Task errors

Surface errors were recorded in 99 trials: 39 large/narrow trials (3.2 ± 4.3) and 60 small/narrow trials (5 ± 4.2). The coder recorded 46 trials with hit errors: 5 large/narrow trials (0.4 ± 0.7), 30 small/narrow trials (2.5 ± 3.1), and 11 small/wide trials (0.9 ± 1.7). Most of the errors were observed when standing on the narrow surface and fitting the block to the small opening.

Figures 3 and 4 show box and whisker plots of errors. The median (middle quartile) shows the midpoint of the data and is displayed by the line that divides the box into two sections. Half the errors were larger than or equal to this value, and half were less. The middle “box” characterizes the middle 50% (2*interquartile range [IQR]) of error for each condition. The error bars show 1.5*IQR higher than the third quartile (less than 3*SD). Note that none of the participants made errors beyond 3*SD higher than the mean (or median line), so we did not have any outliers (Figure 3 and 4).

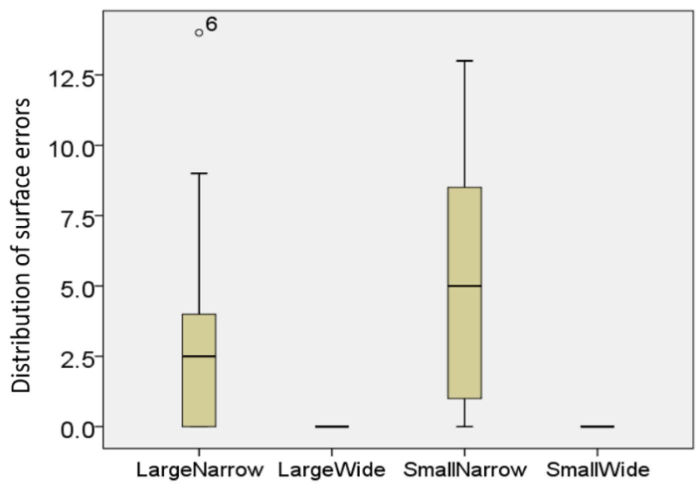

Figure 7. Distribution of trials with surface errors.

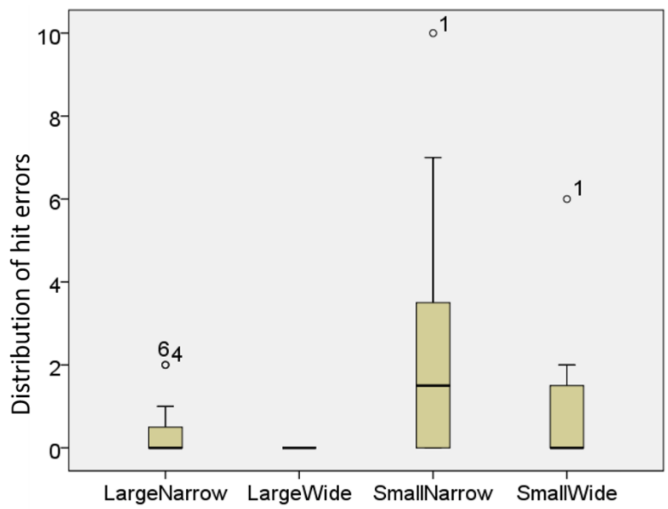

Figure 8. Distribution of trials with hit errors.

4.4.2 Control strategies—the variability structure among joint angles

We observed DVz did not change across conditions in the hold phase to stabilize both CoM and hand position. Contrary to our expectation, we did not observe an interaction between opening and support surface size on hand DVz, $F(1,11) = 0.073$, $p = 0.395$, $\eta^2 = 0.073$, or CoM DVz, $F(1,11) = 0.173$, $p = 0.686$, $\eta^2 = 0.017$. No main effect of surface size was observed in the hand DVz, $F(1,11) = 1.053$, $p = 0.329$, $\eta^2 = 0.095$, or CoM DVz, $F(1,11) = 0.933$, $p = 0.357$, $\eta^2 = 0.085$. There was no main effect of opening size on hand DVz, $F(1,11) = 0.023$, $p = 0.683$, $\eta^2 = 0.023$, CoM DVz, $F(1,11) = 0.002$, $p = 0.966$, $\eta^2 = 0.001$, (Figure 5).

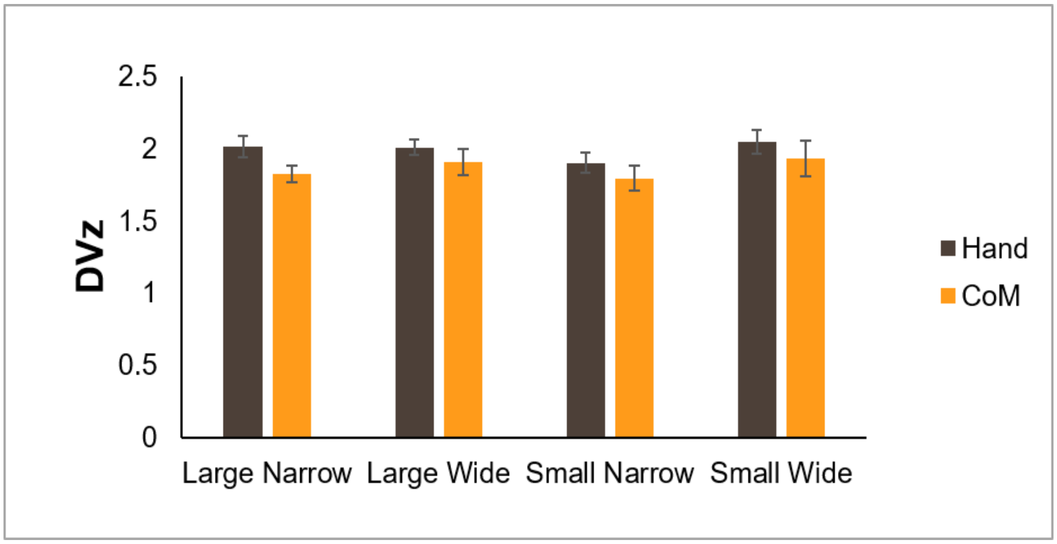

Figure 9. CoM and Hand DVz. Error bars are SEM.

The components of variation in the UCM subspace revealed some significant differences. We observed a significant interaction between opening size and support surface width for CoMVucm, $F(1,11) = 7.933$, $p = 0.018$, $\eta^2 = 0.442$, and HandVucm, $F(1,11) = 7.882$, $p = 0.019$, $\eta^2 = 0.441$. The highest Vucm was observed when standing on the wide surface, suggesting the adoption of a flexible control strategy only in the small/wide condition. We did not observe a main effect of opening size on CoMVucm, $F(1,11) = 3.456$, $p = 0.093$, $\eta^2 = 0.257$ or HandVucm, $F(1,11) = 4.555$, $p = 0.059$, $\eta^2 = 0.313$. There was no main effect of support surface size on CoMVucm, $F(1,11) = 0.716$, $p = 0.417$, $\eta^2 = 0.067$, or HandVucm, $F(1,11) = 0.545$, $p = 0.477$, $\eta^2 = 0.052$. Therefore, Vucm for both the CoM and hand were invariant when standing on the narrow surface, for both small/narrow and large/narrow conditions, suggesting a less flexible control strategy for the control of body CoM and hand (Figure 6).

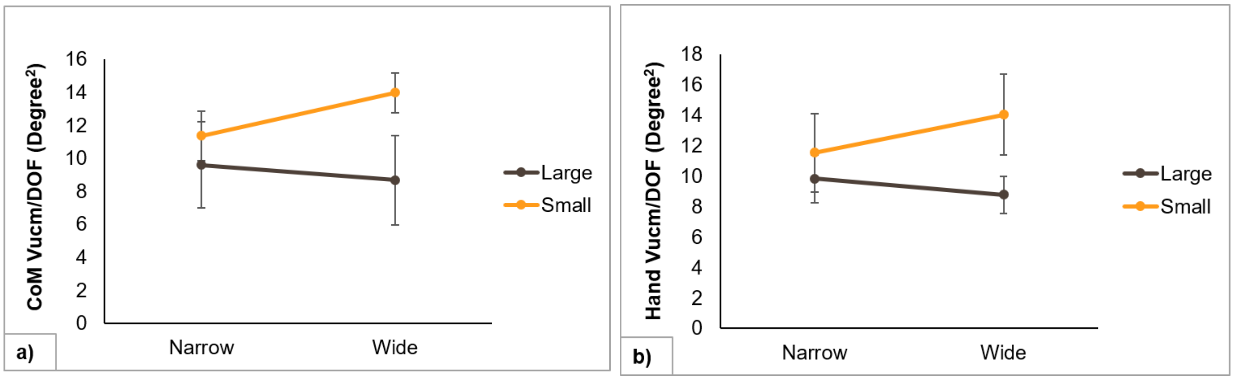

Figure 10. a) HandVucm and b) CoMVucm. Error bars are SEM.

Contrary to our expectation, we did not observe interactions between opening and support surface size in CoMVort, F (1,11) = 0.247, p = 0.629, η^2 = 0.022, and in handVort, F (1,11) = 0.101, p = 0.757, η^2 = 0.009. Despite the average of handVort and CoMVort was increased when standing on the narrow support surface, handVort = 0.17 and CoMVort = 0.26, compared to when standing on the wide support surface, handVort = 0.11 and CoMVort = 0.18, the support surface size effect did not reach statistical significant in handVort, F (1,11) = 1.476, p = 0.250, η^2 = 0.118 and CoM Vort F (1,11) = 0.665, p = 0.432, η^2 = 0.057. We only observed a main effect of opening size on handVort, F (1,11) = 9.142, p = 0.012, η^2 = 0.454, while a main effect of opening size on CoMVort was not observed, F (1,11) = 1.545, p = 0.240, η^2 = 0.123, (Figure 7).

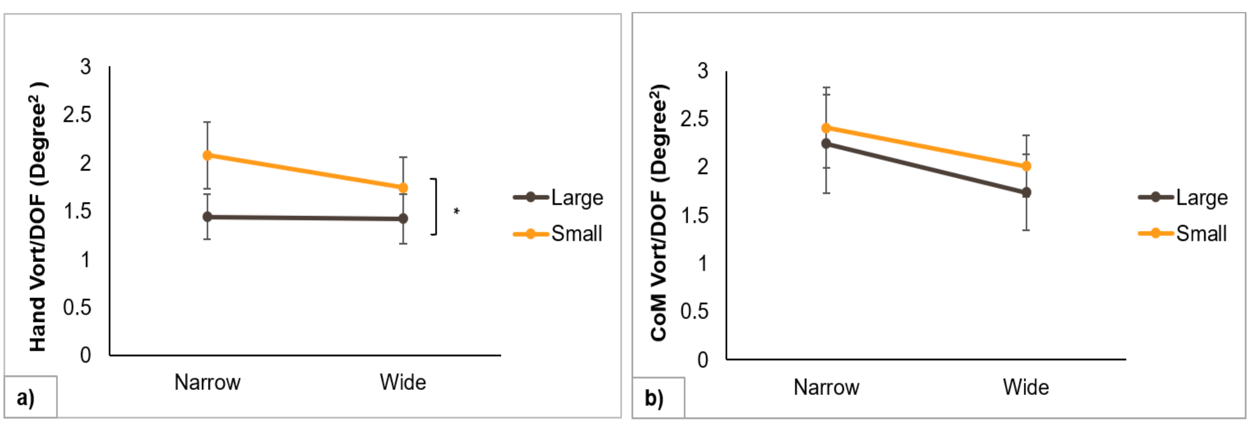

Figure 11. a) HandVort and b) CoM Vort. Error bars are SEM.

4.4.3 Control strategies –end effectors

Contrary to our expectation, there was no interaction between opening and surface size on CoMSD, $F(1,11) = 3.862$, $p = 0.075$, $\eta^2 = 0.260$, or handSD, $F(1,11) = 0.276$, $p = 0.610$, $\eta^2 = 0.024$. Rather, we observed a significant main effect of support surface size. The CoMSD was larger when standing on a narrow support surface, $F(1,11) = 23.488$, $p = 0.001$, $\eta^2 = 0.681$. The handSD was increased, $F(1,11) = 14.762$, $p = 0.003$, $\eta^2 = 0.573$) when standing on a narrow support surface. There was no significant effect of opening size on CoMSD, $F(1,11) = 0.748$, $p = 0.406$, $\eta^2 = 0.0064$), whereas, fitting the block to the small opening increased the handSD, $F(1,11) = 7.516$, $p = 0.019$, $\eta^2 = 0.406$. These findings indicated smaller end effector variability (both CoM and hand) in the small/wide condition (similar to the control condition with a large opening and wide surface), while both the small/narrow and large/narrow conditions demonstrated larger end effector variability (Figure 8).

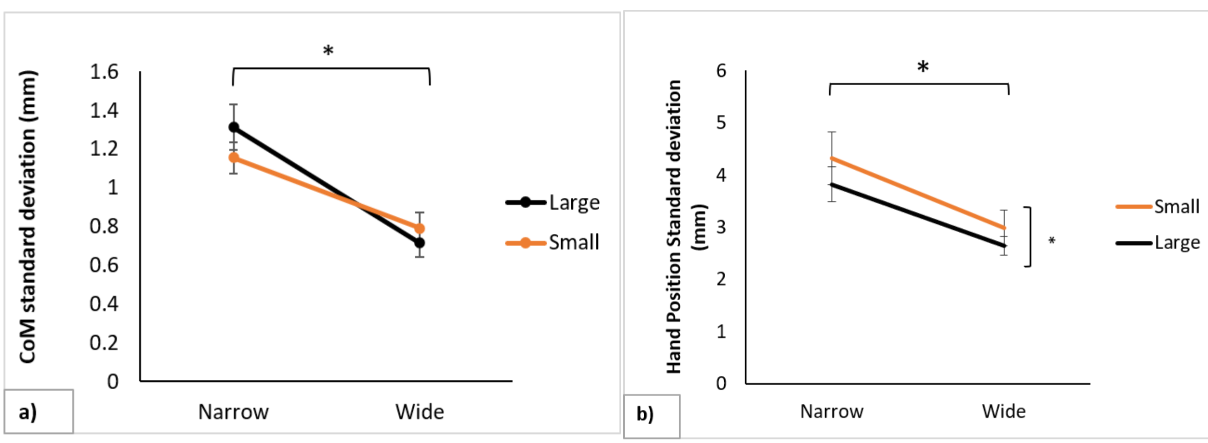

Figure 12. a) CoMSD and b) handSD during the hold phase. Error bars are SEM.

4.5 Discussion

This is the first study to explore the extent to which healthy young adults change control of their strategy when performing a postural manual task while changing task constraints. Our results indicate that a flexible strategy is not ubiquitous in young adults. Rather, the adopted control strategy appears to be driven by the constraints imposed on posture. When the postural constraint was more difficult in the small/narrow and large/narrow conditions, a less flexible control strategy emerged. Whereas, in the less challenging postural condition, a more flexible strategy emerged in the small/wide condition. We believe the reason the control strategy emerges based on postural challenge is because the consequences associated with failing to successfully perform the postural task (e.g., falling) are more severe than the consequences of making a manual error.

Both the UCM and basic variability metrics support the aforementioned interpretation. In both conditions with a difficult postural constraint (small/narrow and large/narrow), the Vucm of both the hand and CoM were invariant. There was an increase in CoM and hand Vort when standing on the narrow surface, but results did not reach statistical significance. Given that an increase in Vort can raise the variability of the end effector (Scholz et al., 2001), we found an increase of Vort was translated to a higher variability of the hand and CoM variability. Additionally, the DVz results suggested relative changes among Vucm and Vort remained invariant across conditions, further demonstrating the importance of postural control. The high DVz across conditions means the strength of the control strategy when standing on the narrow support surface (in small/narrow and large/narrow conditions) was preserved just as high as when an individual is standing on the wide support surface (in small/wide condition).

Standing on the narrow surface was not an easy task for the participants. We initially expected a flexible control strategy to appear if in the condition where only posture was challenged (the large/narrow condition), much like what we observed in the condition where only manual control was challenged (the small/wide condition). The rationale for these expectations was that the number of constraints the individual needed to balance with would, in turn, drive the observed control strategy. However, an interaction between the support surface and opening size was not observed; a less flexible control strategy was found in the large/narrow condition, which was contrary to our expectation. Our studies showed that the posture rather than the number of simultaneously performed tasks appeared to influence the control strategy. This is in contrast to previous studies that found no change in CoM variability and Vort, but an increase in Vucm when young participants stood on a narrow support surface (Krishnamoorthy et al., 2005; Hsu et al., 2014). It is plausible that, in the present study, performing a manual task requiring a movement beyond arm's length, would further challenge posture to the point that necessitates the adoption of a more rigid control strategy when standing on a narrow surface. More specifically, the movement performed here shifted the CoM close to the boundary of the reduced base of support. Therefore, the consequence of standing on a narrow support surface was shown to intensify while attempting to fit an object at a far distance, regardless of how large the opening was in front of the individual.

When performing the fitting task on a narrow support surface, adopting a less flexible strategy would simplify control since the immobilization of joints would reduce motor abundance. A less flexible control strategy would, therefore, resemble what is observed in studies where joints are immobilized. In fact, immobilization studies have generally found Vucm decreases and Vort increases when joints are braced (Hsu et al., 2014). In the present study, the central nervous system freezes the movement of the joints to exert tighter control over movement and restrict the perturbing effect of torques, which can be induced by increasing the joints variability and negatively influence the performance of the postural manual task (Hilt et al., 2016). It is likely that increases in muscle co-contraction is a stabilizing strategy to attenuate the perturbing effects of torques arising from body movements (Gribble et al., 1998). Co-contraction is also a strategy that facilitates the accuracy of multi-joint arm movement. Higher co-contraction, for example, has been observed when reaching to small targets (Gribble et al., 2003), and is positively correlated with higher accuracy of the proprioception (Craig et al., 2016). It is also proposed that the shift from the spinal to supra-spinal and cortical control levels occurs when co-contracting muscles while standing on an unstable surface (Alizadehsaravi et al., 2020). Overall, the use of muscle co-contraction is likely the conscious adaptive mechanism for the less flexible control strategy.

4.5.1 Falling consequence explained the driving role of postural constraint

The consequence of failing to properly control posture (i.e., falling) may explain the specific control strategy that was observed when standing on a narrow support surface. Depending on the consequence of the task, the control strategy was functioning in the configurations that increase the chance of task success. In the less flexible control strategy, the difficulty of standing on a narrow surface was high, and the body DOF were organized to prevent falling. Often, even the perception of balance consequences can alter postural control strategy. For example, in studies where participants were asked to stand on elevated surfaces, a stiffer and less flexible control strategy was adopted. Whereas, in participants not fearful of falling, standing on an elevated surface did not increase postural variability. Thus, stiffer posture was not observed (Davis et al., 2009). Similar changes in postural strategy have also been observed in construction workers when working at an elevated height (Simeonov and Hsiao 2001). Thus, in our task as well as previous research, it appears both actual and perceived postural difficulty can drive the postural control strategy. This change in strategy may be explained via resource allocation and priority. Resource allocation, a cognitively based argument with extensive roots in the postural literature, has been used to explain observed postural control strategies when performing dual and multi-task activities. For example, greater regularity of postural sway (indicating a stiffer posture) was observed in a unilateral stance compared to a bilateral stance despite the increased precision demands of a concurrent force matching task. The higher regularity suggests more cognitive resources were diverted to postural control (Huang et al., 2010). Thus, when postural challenges can destabilize, more resources are diverted to maintaining balance. In the current study, this was achieved through the adoption of a less flexible control strategy. In contrast, when posture was not challenged, a more flexible strategy was adopted. The higher flexibility inherent in this strategy means some joints were freed from the control (Scholz et al., 2001), and greater flexibility was elicited to perform the task (Kim et al., 2012).

4.5.2 Conclusion

In the present study, we found the flexible control strategy is not ubiquitous in young adults. We found that a more challenging postural constraint (i.e., standing on the narrow surface) would elicit a less flexible control strategy in a postural manual task and would determine the adopted strategy. We mentioned that the central nervous system made some effort to limit any extraneous joint motion by muscle co-contraction when standing on a narrow surface. The actual and perceived falling consequence of postural constraint appeared to increase the notion of postural control and explained our findings.

4.5.3 Future directions

In this study, as discussed above, we believe task prioritization and consequences may have influenced the adoption of a control strategy. Given the shared resources between posture and manual task, the competition for allocating the resources may have occurred. If so, the postural task priority would have happened. When a task is prioritized, the more demanding task requires a greater investment of resources while the secondary task performance declines (Simon-Kuhn et al., 2019). For example, increasing the difficulty of gait tasks (walking to stair climbing) did affect the manual task (i.e., holding a tray with a cup of water) (Madehkhaksar et al., 2016). Performing more complex walking with obstacle crossing decreased the verbal task performance (Siu et al., 2008; Raffegeau et al., 2018). Typically, the cost of adding a task was assessed to inform about the prioritized task. However, in the present study, we did not measure the cost of adding a postural or manual task to our dependent variables, meaning the speaking about task priority needs further research. In the next chapter (manuscript 2), we explore how tasks are prioritized when performing a standing manual task.

CHAPTER 5. MANUSCRIPT 2: TASK PRIORITIZATION IN POSTURAL MANUAL TASK

5.1 Abstract

In daily life, maintaining an upright stance frequently occurs while performing a concurrent manual task, such as reaching. Studies examining the integration between posture and manual control have been conducted to assess changes in postural stability under these types of dual-task conditions (Haddad et al., 2010). Typically, posture is considered to have priority over the concurrent performance of other tasks. However, both postural and manual tasks can have consequences if they are executed poorly. The consequences of not performing a task appropriately can influence how the nervous systems prioritizes the individual component tasks. Typically, if one task, such as posture, is prioritized, other concurrent tasks' performance can decline (Shumway et al., 1997). In this study, we examine task prioritization in a postural manual task. This specific paradigm was chosen because both manual and postural tasks can have consequences if they are not performed properly. Past dual-tasks studies have demonstrated a reduction in performance when two tasks are performed simultaneously. However, these studies often couple posture with a cognitive task where task failure is not as consequential. Additionally, task prioritization may have influenced the adoption of the control strategy observed in our previous study. The emergence of a less flexible control strategy may be associated with postural prioritization while standing on a narrow surface since safety and balance was important during this condition. In contrast, the flexible control strategy may have signaled manual prioritization while standing on a wide support surface and fitting a block to a small opening. Here, the main objective was to investigate how changing postural and manual task constraints determines task prioritization.

Participants performed a postural manual task while standing on a wide or narrow surface and fitting a block to a small or large opening. We examined whether the postural or manual task was prioritized by calculating a dual-task cost (DTC) for the center of pressure (CoP) and hand variability. When participants were standing on the wide-support surface and fitting to the small opening, the hand and CoP Variability DTC were not significantly different, signifying no task priority. In contrast, higher hand Variability DTC than CoP Variability DTC when standing on the narrow surface in a condition with or without a manual challenge (fitting to either small or large opening) exhibited higher postural priority. Therefore, it appears that balance is prioritized over manual control when the postural task has consequences.

5.2 Introduction

In routine life, maintaining balance frequently occurs while a concurrent manual task, such as reaching, is being performed. A dual-task paradigm requiring a person to perform a postural and manual task concurrently has been used to examine task performance when both the postural and manual control systems are challenged (Trivedi et al., 2010). For example, posture is stabilized when performing a manual task that requires precision, suggesting that postural stability facilitates manual control (Haddad et al., 2010). Additionally, decreases in postural sway are shown to enhance manual control in a light touch paradigm (Lee, Pacheco, & Newell, 2019). On the other hand, when posture is unstable, such as when standing on a compliant surface and grasping an object, postural sway is reduced to provide more stable balance (Voudouris et al., 2013). To date, most dual-task posture studies have focused on examining changes in postural control. While both postural and manual tasks are well-learned over the human life span, both have consequences if poorly executed, including loss of balance or dropping a valuable object. Consequences may drive prioritization in a manner where the task with the least consequences of failure exhibits the most significant decline in performance. In this study, we examine how both a postural and manual task is prioritized when each has a salient metric of performance (and failure) to the participant. Investigating task priority can provide a better understanding of how the nervous system strikes a balance between safety and mobility (Yogev-Seligmann et al., 2012).

Much of what we know about performing a postural and concurrent task comes from studies where individuals perform a postural-cognitive (Yogev-Seligmann et al., 2008) or gait-manual (Plummer-D'Amato et al. 2012) task. The interference between postural control in standing or walking with the secondary task suggested that task consequences significantly affect performance (Nordin et al., 2010). Competition of resources between tasks can result in a decline in performance, especially in the cognitive task (Doumas et al., 2008), which may be due to the consequences of failure. Specifically, cognitive task failure in the typical paradigm may have fewer consequences than losing one's balance. Dual-task cost (DTC) is often calculated to quantify task priority (Raffegeau et al., 2018). The higher the cost of one task, reflected in a decrease in performance relative to a baseline trial, suggests the task has less priority (Doumas et al., 2008). Likewise, when the manual task was challenged in a walking manual task, one study found the DTC for step length and velocity increased when performing a more complex manual task (carrying pitchers with water on a tray). The higher manual task challenge lowered gait performance (Abbruzzese et al., 2014). Similar findings were observed in other carrying tasks requiring precision (Asai et al., 2014; Nordin et al., 2010). On the other hand, when gait is more complex and potentially more hazardous in regards to task failure, such as climbing stairs, manual task performance declined (Madehkhaksar & Egges, 2016), possibly due to prioritizing posture and balance over the secondary task. Prioritizing posture over other tasks is widely found in the literature and is often referred to as a posture-first strategy (Bloem et al., 2001; Woollacott & Shumway-Cook 2002).

When applied to a postural manual task, like in a standing and fitting task, the association between task consequences, performance, and prioritization has not been examined. It is possible that the findings from a standing postural task will not be equivalent to previous literature examining dual-task walking, given the dynamics of gait are very different compared to static stance. Specifically, gait is inherently less stable than standing given periods of single support and times when the COM is outside of the base of support. A manual task may therefore be less prioritized during gait. In essence, the posture first strategy may not be observed in a dual-task static standing behavior.

In this regard, task prioritization may have influenced the difference between condition control strategies observed in the previous study. Changes in control strategies may depend on which task is prioritized. Specifically, a less flexible control strategy may suggest that the postural task is prioritized (e.g., standing on the narrow surface). In contrast, a flexible control strategy may signify manual prioritization. Here, we will address the relationship between task prioritization and postural manual task performance.

In the current study, we used the same postural and manual challenges as the previous study. Like the past work, we expect prioritization to change as task challenges increase (Raffegeau et al., 2018; Simon-Kuhn et al., 2019). In previous studies, changes in movement variability were used to quantify the cost to show the cost of standing during a postural cognitive task (Doumas et al., 2009). Given the evidence of changes in the variability as a proxy of performance in dual tasks (Huxhold et al., 2006; Doumas et al., 2009; Boisgontier et al., 2013), the variability of the end effectors was used in this study. We had combination of standing on narrow/wide surface and fitting a block to a large/small opening. We assessed DTC variability in the small/narrow, small/wide and large/narrow conditions for hand and CoP. We used the wide/large condition as a baseline for the DTC calculations for two end-effectors: hand and CoP.

This study aimed to investigate how changes in the difficulty of the postural or/and manual task determines the priority of either task. Because we added challenges to each condition, we expect there will be higher DTC for both end effectors compared to the baseline condition (large/wide condition without any challenge). Our first hypothesis is a higher postural and manual costs in challenging conditions than the baseline condition. Secondly, because in the small/wide condition, only the manual task is challenged, we expect manual prioritization while holding the block within the small opening and standing on the wide surface. Note that the flexible control strategy we observed in our previous study means that the posture may have facilitated the manual task, and thus, invested more priority in manual control. Our second hypothesis is that when standing with only a challenging manual task (in the small/wide condition; CoP DTC > hand DTC); there will be a greater postural than manual cost. Thirdly, since the postural task is challenged, we expect posture will be prioritized in the small/narrow and large/narrow conditions. In the small/narrow condition, where both tasks are difficult, we expect higher postural priority. Note that, since we previously observed a less flexible control strategy in both small/narrow and large/narrow conditions, we expect the allocation of resources to the postural task is likewise in these two conditions. Our last hypothesis is a higher manual than postural cost when standing on the narrow surface (in the small/narrow and large/narrow conditions; hand DTC > CoP DTC).

5.3 Methods

5.3.1 Participants

Twenty-three healthy young individuals (23.95 ± 3.47 years, 16 females and seven males) participated in the study. We used 12 participants' data from the first study. All participants signed a consent form approved by the Purdue University institutional review board. All participants were free of any prior history of orthopedic or neurological disease according to their self-declarations.

5.3.2 Apparatus

Participants stood on an adjustable support surface (5 cm height), their feet at shoulder-width distance apart. Foot position was marked so that participants adopted a similar stance between trials. The fitting board used to perform a manual fitting task was located at 4/3 arm length. A block used to perform the fitting task was placed on an adjustable table to the participant's elbow height. The block was placed on top of the table, under the hand (with the arm flexed at 90°). The MotionMonitor software synchronized a Vicon Motion Capture system and AMTI force plate.

5.3.3 Procedure

Before testing, we explained all procedures to the participants. We measured their arm length, foot length, height, weight, participant age, gender, and dominant hand. Next, we outfitted the participant with retro-reflective marker clusters placed on the right and left hand, forearms, upper arms, upper back, lower back, head, waist, thighs, calves, and feet.

Participants were instructed to pick up a block (81 cm^2, 50 g) and fit it into a small (121 cm^2) or large (196 cm^2) opening while standing on a narrow (1/3 of foot length) or wide (50 x 50 cm^2) support surface. The block was first grasped and transported to an opening in the fitting board (transport phase) and then held within the board for five seconds (hold phase). After the hold phase, participants returned the block to the table. Participants were instructed to avoid making either hit or surface errors. A hit error was defined as any contact of the block with the perimeter of the opening, and a surface error was any wobbling of the support surface. If any of these errors occurred, participants were told to fix the error and continue with the trial. Three familiarization trials were practiced before the start of the data collection.

We had a combination of two surface sizes (narrow and wide) and two opening sizes (small and large). Each condition had a unique challenge: small/narrow (postural and manual challenges), large/narrow (postural challenge), small/wide (manual challenge), and large/wide (no challenge as baseline condition). Each condition was performed for 40 trials.

5.3.4 Data analysis

We analyzed the center of pressure (CoP) excursions and the position of the hand marker in three dimensions. All data were captured at a 250-Hz sampling rate and filtered with a fourth-order Butterworth (12-Hz low-pass, zero-lag) filter. We used Matlab, version 2018, for our data analysis.

Each trial was separated into two phases (transport and hold). Phase separation was conducted using the velocity profile of the hand marker. We conducted all data analysis for the hold phase only. In the hold phase, the participants were steady, and we were able to average the data, whereas, in the transport phase, the temporal changes in the task dynamics could impose high variation on averaged data. The hold phase started at 5% of the maximum hand velocity while transporting the block. The hold phase's termination was at 5% of the maximum velocity when returning the block to the table.

We randomly selected 20 trials without any hit or surface error for all of the data analysis. We selected only successful trials to be sure that participants' motor behavior was consistent across trials. Including trials with errors would make a different behavior of participants, and therefore, we would be unable to conduct a variability analysis across trials. To exclude trials with hit errors, two coders watched the synchronized video. Any trial where the LED illuminated, flickered, or flashed was coded as a trial with a hit error. We conducted Cohen's kappa test of agreement on hit errors between two coders on 23 participants, for all four conditions, and 40 trials in each condition. There was a strong agreement between the two coders ($p < 0.001$). The Cohen's kappa agreement between two coders was $k = 0.913$ for large/narrow, $k = 0.920$ for small/narrow, and $k = 0.908$ for small/wide. We used only the first coder records to exclude trials with hit errors and perform all data analysis.

We used a kinematic method to exclude trials with surface errors. The trial with the surface error was determined if the vertical displacement of the foot marker, at any time-normalized percent (normalized to 100%), deviated below 3 times the standard deviation of the mean vertical foot position during the large/wide condition.

We initially calculated the CoP and hand position variability using ellipse area with 95% confidence (Prieto et al., 1996). Then, we calculated DTC as [(Task – baseline)/baseline] x 100 for the large/narrow, small/wide, and small/narrow conditions for two end-effectors ellipse area (hand and CoP). We used the large/wide condition as the baseline condition for all DTC calculations. DTC levels express the effects of the additional task costs (e.g., the additional variability in this study) imposed in the condition with task challenges compared to the baseline task with no challenge. Our dependent variables were DTC for CoP Variability (CoP Var DTC) and hand Variability (hand Var DTC).

To address our hypotheses, first, we used a two-tailed t-test to determine whether DTCs (for hand and CoP) were different from zero (the baseline value). Higher cost than baseline will show an increased variability magnitude than the condition without any challenge (baseline). We also conducted a paired t-test between hand and postural DTCs (hand Var DTC versus CoP Var DTC) to determine the priority of either postural or manual tasks. Higher DTC for either end effector means that less priority was observed in the end effector. In addition to the CoP and hand Var DTC, we used the number of task errors (surface error and hit error) to show each task condition's accuracy and consequence. Note that the number of errors was counted during the whole testing (160 total trials), but the Var DTC for both hand and CoP was calculated during randomly selected successful trials. The p-value was significant at $p < 0.05$.

5.4 Results

5.4.1 Postural and manual costs compared to the baseline

Error trials

Surface errors were recorded in 145 trials: large/narrow = 65 trials (2.82 ± 0.73) and small/narrow = 80 trials (3.47 ± 0.77). The coder recorded 73 trials with hit errors: large/narrow = 13 trials (0.56 ± 0.19), small/narrow = 45 trials (1.95 ± 0.52), and small/wide = 15 trials (0.65 ± 0.29).

CoP and hand variability DTC

In the paired t-test comparing the CoP Var DTC to the hand Var DTC, a significantly higher hand Var DTC than CoP Var DTC was evident in the small/narrow condition, $t(22) = 2.889$, $p = 0.009$, and in the large/narrow condition, $t(22) = 2.758$, $p = 0.011$. The hand Var DTC was 42% and 35% higher than the CoP Var DTC in the small/narrow and large/narrow conditions, respectively. We did not observe any significant difference between the CoP and hand DTCs in the small/wide, $t(22) = 1.580$, $p = 0.128$ (Figure 1).

In the two-tailed t-test comparing the DTCs to the baseline, DTCs were significantly higher than zero for the hand and CoP Var in the small/narrow and large/narrow conditions. The hand and CoP Var DTC were not significantly higher than zero in small/wide conditions. More details about the CoP and hand Var DTC two-tailed and paired t-tests are in and Figure 1.

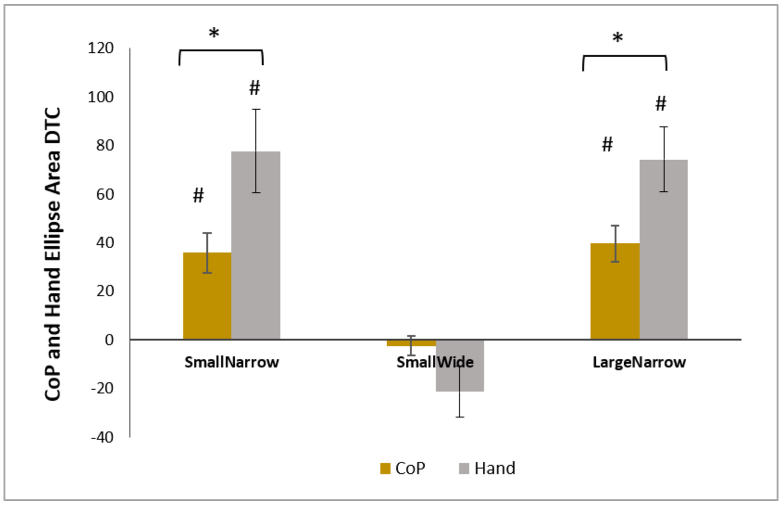

Figure 13. CoP and Hand Var (Ellipse Area) DTC. (*) indicates the significant difference between postural and manual DTCs. (#) indicates DTC was significantly different from baseline condition (zero). Error bars are SEM.

Table 1. Two tailed t-test results for the Var DTC in comparison to the baseline. (*) indicates p < 0.05.

	t	p-value	Mean difference
CoP Var DTC small/narrow	4.401	0.001*	35.934
CoP Var DTC small/wide	0.617	0.543	-2.419
CoP Var DTC large/narrow	5.345	0.001*	39.712
Hand Var DTC small/narrow	4.513	0.001*	77.712
Hand Var DTC small/wide	2.040	0.054	-21.268
Hand Var DTC large/narrow	5.552	0.001*	74.325

5.5 Discussion

The present study is the first to characterize how one task is prioritized, and resources are allocated among two motor tasks: postural and manual. We observed when only manual task is challenged in the wide/small condition, there is no priority for manual control. The consequence of fitting to the small opening was so minimal that the DTCs did not change relatively and compared to the baseline condition. Whereas when posture is challenged, the postural control was prioritized, regardless of the necessary precision. The cost of standing on the narrow surface was so high in the large/narrow and small/narrow conditions that both hand and CoP DTC were higher than baseline, and hand Var DTC was higher than CoP Var DTC. Notably, in the small/narrow condition and despite high precision demand, standing on the narrow surface increased the cost of hand control than postural control, to the extent that higher priority for postural control was required. The hand Var DTC increased by 42% and by 35% than the CoP Var for the small/narrow and large/narrow conditions, respectively.

In light of these findings, we understood the task priority is inherent to the task consequences. The notion of task consequence specifically appeared when falling is a consequence. Perhaps, in the small/narrow and large/narrow conditions with a high risk of falling, the need for a stable postural control was so high that there was a greater preference to accommodate balance control. Notably, the consequence associated with deteriorated posture, such as falling, was higher than the consequence of losing the accuracy of manual task control (fluctuating the block within the opening). We understood that the prioritization of postural control was necessitated, despite the need for precision. Thus, in a competition between postural and manual control, the central nervous system's control invested more resources in maintaining balance control than in manual control. Nevertheless, prioritizing the task with the higher consequence was not universal. We initially sought to detect higher manual task priority when hand control is challenged by smaller opening size. However, in the small/wide condition, neither tasks were prioritized. Despite this, it was likely that the manual task's consequence was not hazardous enough to necessitate manual task priority; we implied that the priority for the manual task often mattered less compared to the concurrent tasks. Likewise, in a competition between manual and cognitive tasks, a higher priority is invested in communicating speech tasks (Kuhn et al., 2019).

The notion of postural priority's primary interpretation is that in response to a destabilizing postural challenge, healthy young adults utilized maximal postural reserve (capability to respond effectively to the postural threat) to avoid falling while performing the concurrent task. When an individual reaches the postural reserve limit, the hazard estimation of losing postural control necessitates the higher postural priority (Yogev-Seligmann, Hausdorff, & Giladi, 2012). We understood that in the competition between postural and the concurrent manual tasks, the participants had a higher hazard estimation for losing at the postural task, and therefore, prioritized postural control. Previous studies have used a similar analogy to show the "posture-first" strategy in the dual-task postural cognitive paradigm (Bloem, Valkenburg, Slabbekoorn, & Willemsen, 2001). Note that in the postural cognitive task, the competition was over a limited pool of resources distributed between postural and cognitive tasks (Boisgontier et al., 2013; Doumas & Krampe, 2015; Riley, Baker, Schmit, & Weaver, 2005; Siu & Woollacott, 2007). While in this study, the shared resources were distributed between the control of two motor tasks incorporating changes in joint angles or muscular activity. However, our findings agree with rationale of previous studies using the postural cognitive paradigm. The rationale could be related to the neural control of the postural and manual task. Postural control is an overtly practiced task in our daily life that often benefits from automatic control (Takakusaki et al., 2017), while the manual task is goal-directed, requiring some planning and cognitive processes (Archambault et al., 2009). The difference between the neural processes may also demonstrate how a postural control priority brought up automated control for posture. Overall, in the postural manual task, it appears the primary factor for allocating priority to one motor task is related to postural task's perceived consequence and estimation of falling hazard.

Relating to our first manuscript, when posture was destabilized, and there was a falling consequence, the less flexible control strategy stiffened the body to induce a higher postural priority. The less flexible control strategy indicated that the variability among joint angles was strictly controlled, and the end effector variability for hand and CoP increased. Note that the variability was more increased for the hand rather than the CoP, perhaps to conduct the cost of standing on the narrow surface to the hand end effector. This behavior could compensate the effect of standing on the narrow surface to some extent, however, it can still leave the performer vulnerable to challenges. Nevertheless, the motor control system accepts this cost to stabilize posture and avoid falling.

Interestingly, the flexible control strategy demonstrated in our previous manuscript for the wide/small condition did not require any task prioritization. In the flexible control strategy, the participants increased the variability among joints that do not affect the end effector to facilitate hand control (Hsu & Scholz, 2012). Here, despite the hand Var DTC being smaller than the CoP Var DTC, the difference did not reach a significant level. Thus, the manual task priority was not necessitated. However, both of DTCs were reduced relative to the baseline condition (large/wide condition) without reaching statistical significance, which to some extent, supports the studies indicating that posture is stabilized to facilitate hand control. Despite this finding not being strongly supported in this study, it is in line with the established interpretation that posture is stabilized to facilitate the manual task when precision is needed (Haddad et al., 2010).

5.5.1 Conclusion and future research

This study documented the intricacies in prioritizing postural and manual tasks. We found that falling consequences primarily manipulated the allocation of resources. When postural control was destabilized over the narrow support surface, although the manual task required high precision, the need for stable balance control drew more priority. However, when there was only the consequence of losing the manual task's accuracy, the central controller did not allocate higher priority for either task. Altogether, the hazard estimation perceived for performing a postural task is the main factor determining task prioritization.

Because we found postural prioritization and changes in the control strategies when both postural and manual tasks are challenged, it is important for future research needs to investigate the role of posture. The adjustments prior to fitting the block would have some potentials to reveal further about the changes in favor of postural control. Given that the variability among multiple DOF was structured to control posture (Hsu & Scholz, 2012), the synergies' behavior has the potential to show how constraints can play a significant role in organizing synergies prior to reaching the target. In the third study (Manuscript 3), we will investigate this new research question.

CHAPTER 6. CONCLUSION

This dissertation examined the emerging control strategies, and task prioritization as we altered the constraints of a postural manual task. Young college students participated in the postural manual task with four conditions: stand on a wide or narrow surface and fit a block to a small or large opening. The findings raised our understanding of the postural manual behaviors about 1) the effect of constraints on adopted control strategies, and 2) the effect of task prioritization in the challenging postural manual task.

6.1 Specificity of control strategies to the task demands in postural manual task

In this study, we observed task-specific behavior of control strategies (i.e., at the level of coordinating joint angles) to the challenges associated with the postural manual task. The flexibility of the control strategy was examined with the UCM analysis and the end-effectors variability (see chapter 4). Our findings revealed that the flexible control strategy was utilized to satisfy the precision demands of fitting to the small opening when standing on a wide surface. Therefore, participants took advantage of the motor redundancy and explored the best solutions with a flexible control strategy. Whereas the less flexible control strategy was taken when standing was challenged in the postural manual task. Therefore, the need for higher postural stability made the motor system switch to the less flexible control strategy. We found the flexible control strategy in higher Vucm for stabilizing hand and body CoM (chapter 4, Figure 6), smaller hand and CoM standard deviation (chapter 4, Figure 8), when standing on a wide surface. In contrary, during the condition with a narrow support surface, the higher postural demand required participants to minimize unnecessary destabilizing movements. Therefore, the motor system constrained variation among DOF in a less flexible control strategy (see chapter 4). The less flexible control strategy was revealed in the reduced Vucm for stabilizing the hand and body CoM (chapter 4, Figure 6), and greater hand and CoM standard deviation (chapter 4, Figure 8) when standing on the narrow surface. Adoption of the less flexible control strategy resists against exploiting motor redundancy and does not allow the motor system to channel enough variance to the Vucm to stabilize the task end effector (Hsu et al., 2014; Olafsdottir, Yoshida, Zatsiorsky, & Latash, 2007). Although the less flexible control strategy may constrain variability among joint angles, and the perturbations may expose the participant to the falling, our findings revealed that it is a robust control strategy against perturbation. We found that participants recruited strong synergies (high DVz, see chapter 4, Figure 5) to provide high stability for CoM and hand control.

Our initial study raised an important follow-up question. Because we inferred the flexible control strategy was more beneficial in the condition with a stable surface and the less flexible control strategy was utilized when standing on a destabilizing surface in a postural manual task, we understood there might be a priority for one task (either postural or manual) that can be associated to the roles of posture. In the second study, we investigated this question.

6.2 Task prioritization in a postural manual task

In the second study, we documented all intricacies in the prioritization of postural and manual task. When postural control was destabilized over the narrow support surface, despite the manual task required high precision, the postural control draw more priority. We examined the priority for the maintenance of either postural or manual task by computing the dual-task cost (DTC) for the center of pressure (CoP) and hand variability (Ellipse Area). When participants were standing on the wide-support surface and fitting to the small opening, the hand and CoP Variability DTC were not significantly different, signifying no task priority. Alternatively, higher hand Variability DTC than CoP Variability DTC when standing on the narrow surface in a condition with or without a manual challenge (fitting to either small or large opening) exhibited higher postural priority (see chapter 5, Figure 1 and Table 1). Overall, we found that falling consequence and higher hazard estimation for one task manipulates the allocation of resources.

6.3 Innovation

This was one of the first studies elucidated the flexibility among the joint angles can be diminished in healthy participants. We showed when there was a falling consequence in the whole-body reaching task, the motor system utilized the "less flexible" control strategy. This behavior was because the motor control system prioritized postural control over manual task control. Therefore, the controller required the motor system to prominently control balance rather than facilitating the manual task control when the support surface was destabilizing in a whole-body reaching task. This was interesting because typically less flexible control strategy was observed in older adults or participants with some neurological disorders that were incapable of exploiting variability among joint angles. Here, the participants arbitrarily did not exploit variability to prevent falling and to prioritize postural control over manual task.

6.4 Future research and study limitation

Future research should examine the switching between flexible and less flexible control strategies as a function of support surface size. The significant effect of postural constraints will respond to an important question about the role of posture as a control parameter. Control parameters guide the movement system through sequences of stable coordination among components (Bardy, 2004). Exploring the transition between control strategies will demonstrate the surface size that elicits the suboptimal less flexible control strategy and may result in falling.

Previous studies have supported the role of postural constraints as a control parameter. For example, transitions between two modes of coordination emerged between the hip and ankle as a result of change in the support surface in a tracking task (Bardy, 2004; Bardy, Marin, Stoffregen, & Bootsma, 1999; James, 2014), on foam and sway-references surfaces (Creath, Kiemel, Horak, Peterka, & Jeka, 2005), and in postural tracking and scanning tasks (James & Newell, 2011). However, these studies only examined coordination at the hip and ankle with a simplified multi-linked control model rather than in a whole-body task with redundant DOF.

In the future study, we can investigate how transitions between control strategies occur as the support surface is scaled. We can specifically manipulate the size of the support surface while fitting to the small opening size. Due to an emergent less flexible control strategy when standing on the unstable surface, we expect an abrupt decrease in the flexibility of the control strategy (CoM and hand Vucm will be decreased) and sudden reduction in the number of synergies (fewer PCs) as the support surface width decreases from 35% to 40% or higher percentage of the foot length when fitting to the small opening.

A limitation of this study was that we needed to have multiple repetitions of performing fitting task per condition. The high repetitions were required for both UCM analysis. The more repetitions also increased the power of analyses for this study. However, multiple repetitions increased the chance of fatigue by the end of testing. To reduce the fatigue effect over final results, we blocked the support surface manipulation and randomized the opening size manipulation within each block. This procedure made every other participant start with the narrow size condition and the next one after with a wide surface. Therefore, some fatigue effect has been canceled across the participants on the results. We think the chance of fatigue effect is minimal on the final results of this study, although may not be vanished completely.

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VITA

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EDUCATION

Purdue University, West Lafayette, IN, USA, 2013-now

Doctor of Philosophy *in Human Motion Control*

Dissertation: *The coordination between postural and manual systems during constrained tasks*

Advisor*: Dr. Jeffrey Haddad*

Tarbiat Modarres University, Tehran, Iran, 2011-2017

Doctor of Philosophy *in Physical Therapy*

Dissertation*: Gait modifications of type 2 diabetes patients following Task-Oriented gait training*

Advisor*: Dr. Farid Bahrpeyma*

Tarbiat Modarres University, Tehran, Iran, 2007-2010

Master *of Physical Therapy*

Dissertation*: The effect of semi dynamic balance training on static balance parameters in patients with diabetic neuropathy*

Advisor*: Dr. Farid Bahrpeyma*

Shahid Beheshti University of Medical Sciences, 2002-2006

Bachelor *of Physical Therapy*

Thesis: The effect of Transcutaneous electrical nerve stimulation (TENS) on the pregnancy rate in women undergoing assisted reproduction technique and embryo transfer.

Advisor: Dr. Naser Salsabili

RESEARCH EXPERIENCES

Purdue University

Ph.D. Researcher

- Examining the coordination between postural and manual control during constrained reaching and standing on different support surfaces (Project Under preparation for pilot study), Purdue University, 2017-now.

- Examining the relationship between imaginary and real movements on postural and manual control (Under preparation article), Purdue University, 2015-now.

- Balance Training in Older Adults to Improve Speech, Stability, Mobility and Quality of Life (Project Under Execution), Purdue University, 2014-now.

- The relationship between balance control during Light voluntarily fingertip touch on a fixed surface and goal directed manual task (Under preparation article), Purdue University, 2014-2015.

Tehran University of Medical sciences

Collaborating researcher

- Road map for of Diabetes research in Iran (Exercise, Rehabilitation and Physical Therapy Research Parts), Tehran University of Medical Sciences, Endocrinology and Metabolism Center, 2012, Tehran, Iran.

Tarbiat Modarres University

Ph.D. Researcher

- The effect of Task-oriented gait training on the walking pattern, cognitive and balance of type 2 diabetes patients with neuropathy. Project for PhD degree, Tarbiat Modarres University, presented December 2016, Tehran, Iran.

Master Researcher

- Validity and reliability of methods for assessing medial foot arch, University of Social Welfare and Rehabilitation Sciences, 2009-2010 (As a chief cooperator).

- The effect of semi dynamic balance training on static balance parameters in patients with diabetic neuropathy. Project for master's degree, Tarbiat Modarres University, Presented January 2010, Tehran, Iran.

Shahid Beheshti University of Medical Sciences

Bachelor Researcher

- The effect of Transcutaneous electrical nerve stimulation (TENS) on the pregnancy rate in women undergoing assisted reproduction technique and embryo transfer. Project for bachelor's degree, Shahi Beheshti University, August 2006, Tehran, Iran.

TEACHING AND MENTORING EXPERIENCES

• Lab instructor of Human Motion control in older adults (HK444), Purdue University, fall 2017, spring and fall 2018, and spring 2019.

• Lab instructor of Lifetime Fitness (PES 111), Purdue University, Summer 2018.

• Lab instructor of Human Motor Development class (HK253), Purdue University, fall 2014, fall 2015, spring 2016, fall 2016 and spring 2017.

• Lecturer and Lab instructor of Human Motor Development class (HK253), Purdue University, spring 2015

CERTIFICATION

• Motor Control Summer School XVI, Summer 2019, Penn State University, USA.

• Big Data: Exploratory Data Mining in Behavioral Research, Summer 2018, Arizona State University, Tempe, USA.

• Nonlinear Methods for Psychological Science, American Psychology Association, Summer 2016, University of Cincinnati, USA.

• Primary Course of Cardiac Rehabilitation (Theory and Practice), 4th -6th September 2007, The University of Social Welfare and Rehabilitation Sciences and Iranian cardiopulmonary Physical Therapy Association, Tehran Heart Center, Tehran, Iran.

PROFESSIONS AND EMPLOYMENTS

• Chief physical therapist of Diabetic patients' Physical Therapy and rehabilitation clinic in Diabetes and Metabolic Diseases Center (2), Tehran University of Medical Science (2012- 2013).

• Physical therapist in Firuzgar hospital, Tehran University of Medical Science (2011- 2012).

• General home-physical therapist, DAM Home-Medical Company, Tehran University of Medical Science (2009-2011).

• General physical therapist in Rahro physical therapy Clinic (2007-2009).

JOURNAL PUBLICATIONS (PEER REVIEWED)

- **Salsabili H**, Ambike S, and Haddad JM. Task prioritization in postural manual tasks (Publication in preparation).
- **Salsabili H**, Ambike S, Munoz-Ruiz M, and Haddad JM. Control strategies during constrained postural manual tasks (Publication under preparation).
- **Salsabili H**, Ryu JH, Ambike S, and Haddad JM. Does light touch enhance manual control? (Publication under preparation).

- **Salsabili H**, Haddad JM, Pajouhi Z, Cai F, Ryu JH, and Zelaznik HN. Does performing an imagined Fitts' law task share similar characteristics to actually performing the task? (Publication under preparation).

- **Salsabili H,** Bahrpeyma F, karimzadeh M, Esteki A. Task-oriented gait trainings improve coordinated muscle activity during walking in Diabetes Neuropathy. Archives of Physical Medicine and Rehabilitation 2016; 97(10); e51.

- **Salsabili H**, Bahrpeyma F, Esteki A. The effects of Task-Oriented Motor Training on gait characteristics of patients with type 2 diabetes neuropathy. Journal of Diabetes & Metabolic Disorders 2016; 15:14.

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- Salsabili N, Nakhostin Ansari N, Berjis K, Sedighi A, **Salsabili H**. Effects of physiotherapeutic TENS in a woman with unexplained infertility. Physiotherapy Theory and Practice, 2010; 26(6):1–5.

CONFERENCE PRENTATIONS

- **Salsabili H**, Haddad JM, Munoz-Ruiz M, and Ambike S. The impact of constraint severity on the coordination of simultaneous postural and manual tasks. Progress in clinical motor control I: Neurorehabilitation, 23rd- 25th July 2018, State college, Pennsylvania, USA (Poster Presentation).

- **Salsabili H**, Ambike S, Munoz-Ruiz M, and Haddad JM. Postural strategies when performing a manual task on an unstable support surface. North American Society for the psychology of sport and physical activity**,** 21st– 23June 2018, Denver, Colorado, USA (Oral Presentation).

- Liddy, J. J.**,** Rooney, L. J., Romine, N. L., Cho, H., Arnold, A. J., **Salsabili, H.**, Cui, C., & Haddad, J. M. Does holding an object benefit the performance of a standing precision manual task? International Society for Posture and Gait Research, July 2017, Fort Lauderdale, FL, USA (Poster Presentation).

- **Salsabili H**, Ryu JH, and Haddad JM. Does light touch enhance manual control? Midwest American Society of Biomechanics, 23-24th Febraury 2017, Grand Rapids, Michigan, USA (Oral Presentation).

- Haddad JM, Snyder S, McDonough M, Rietdyk S, Simon K, Altenburger P, **Salsabili H**, Zauber E, and Huber J. A combined cognitive- and balance-based training intervention for people with Parkinson's disease: COBALT. 4th World Parkinson Congress, 20-23th September 2016, Portland, Oregon, USA (Poster Presentation).

- **Salsabili H**, Huber J, Snyder S, Simon K, McDonough M, Rietdyk S, and Haddad JM. The integration between posture, manual control, and speech in people with Parkinson's disease. 4th World Parkinson Congress, 20-23th September 2016, Portland, Oregon, USA (Poster Presentation).

- **Salsabili H**, Karimzadeh M, Bahrpeyma F, and Esteki A. Task-oriented gait trainings improve coordinated muscle activity during walking in Diabetes Neuropathy. American Congress of Rehabilitation Medicine, 30th October - 4th November 2016, Chicago, USA (Poster Presentation).

- **Salsabili H**, Bahrpeyma F, and Esteki A. Gait modifications of type 2 diabetes neuropathy patients following Task-Oriented motor sequence gait training. World Congress for Neurorehabilitation (WCNR 2016), 10-13th, May 2016, Philadelphia, USA (Oral Presentation).

- **Salsabili H**, Haddad JM, Pajouhi Z, Cai F, Ryu JH, Liddy JJ, and Zelaznik HN. Does performing an imagined Fitts' law task share similar characteristics to actually performing the task? North American Society for the psychology of sport and physical activity, 4th June 2015. Portland, Oregon, USA (Poster Presentation).

- Effects of postural balance training on dynamic stability scores in neuropathic patients with type 2 diabetes. 17th PRM European Congress, 27 May 2010, Venice, Italy (Poster Presentation).

- Spectral characteristics of postural sway in diabetic neuropathy patients participating in balance training. 21th Iranian physiotherapy congress, 11-13 May 2010, Tehran, Iran (Oral Presentation).

- Effect of exercise training on coronary endothelial function and oxidative stress. 16th Congress of Iranian Heart Association in collaboration with American College of Cardiology, 18-21 November 2008, Tehran, Iran (Oral Presentation).

- The effect of transcutaneous electrical nerve stimulation (TENS) on the pregnancy rate in women undergoing assisted reproduction. 18th Iranian physiotherapy congress, 8th – 10th, May 2007, Tehran, Iran (Poster Presentation).

AWARDS and GRANTS

- NSF Funded Travel Grant (summer 2018). Collage of Health and Human Development, Penn State University, State Collage, PA, USA.

- Dale.Hanson Travel Grant (Spring 2018). Department of Health and Kinesiology, Purdue University, West Lafayette, IN, USA.

- Advanced Training Institutes Financial Assistance, American Psychology Association (Spring 2018), Arizona State University, Arizona, USA.

- Dale. Hanson Travel Grant (Spring 2017). Department of Health and Kinesiology, Purdue University, West Lafayette, IN.
- Compton Research Travel Award (Fall 2016). College of Health and Human Sciences, Purdue University, West Lafayette, IN.
- Purdue Graduate Student Summer Grant (Summer 2016), Collage of Health and Human Sciences, Purdue University, West Lafayette, IN, USA.
- Compton Research Methods Award (Spring 2016). College of Health and Human Sciences, Purdue University, West Lafayette, IN.
- Templin Graduate Student Research Award (Spring 2016). Department of Health and Kinesiology, Purdue University, West Lafayette, IN.
- Advanced Training Institutes Financial Assistance, American Psychology Association (Spring 2016), University of Cincinnati, Cincinnati, USA.
- Purdue Graduate student Government General Grant (Fall 2015). Graduate School, Purdue University, West Lafayette, IN.
- Compton Research Travel Award (Spring 2015). College of Health and Human Sciences, Purdue University, West Lafayette, IN.
- Donald L. Corrigan Professional Development Grant (Spring 2015). Department of Health and Kinesiology, Purdue University, West Lafayette, IN.
- Ross Fellowship, 12 months fellowship and three years of assistantship (2014-2017). Graduate School, Purdue University, West Lafayette, IN, USA.
- Top Mater student (February 2010), Tarbiat Modarres University, Tehran, Iran.
- Top Bachler Student (September 2006), Shahid Beheshti university of Medical Sciences, Tehran Iran.

SERVICES

- American Psychology Association membership, 2016-2019
- American Congress of Rehabilitation Medicine membership, 2016-2019
- Faculty representative in Health and Kinesiology Graduate Student Government, Purdue University, 2017-2018
- Health and Kinesiology Senator for Purdue Graduate Student Government (PGSG), Purdue University, 2015-2017
- Member of Grant review Committee at Purdue Graduate Student Government (PGSG), Purdue University, 2015-2017
- Director of events at Iranian Cultural Club, Purdue University, 2014-2015

SKILLS

- Languages: Strong Comprehension in English and Persian
- Computer: MATLAB, SPSS, ENDNOTE.