Effects of Cognitive and Precision Demands on Biomechanical Responses During Manual Lifting Tasks

Thesis

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Abstract

Introduction: Musculoskeletal disorders in the workforce are highly prevalent, especially in material handling operations. In addition to completing physically demanding work, workers must also manage concurrent mental demands present in their tasks. Few studies have examined the effect of concurrent mental demands in occupationally-relevant tasks. This study attempted to fill this void by quantifying the effects of varying degrees of cognitive loads and task precision demands on a material handling task by examining these effects on the kinematics and muscle activity of the trunk and shoulders.

Methods: Twelve subjects lifted and placed a 5 kg box on a rack at one of three destination heights (low, middle, high) while under a simultaneous cognitive load (no load, simple load, complex load) and/or precision constraint (low precision, high precision). Cognitive load consisted of time-based arithmetic questions where participants were tasked with determining the amount of time remaining from a given time to a target time (e.g., Get to 4:00 PM from 3:15 for simple load or get to 4:10 PM from 3:27 PM for complex load). The primary dependent measures were the angular velocities of the trunk and shoulders as well as muscle activity in the erector spinae, rectus abdominus, external oblique, latissimus dorsi, and anterior deltoid muscles.

Results: Significant decreases in angular velocities for both higher cognitive load complexities and higher precision conditions were observed. Additionally, lower 90th percentile normalized muscle activity values were observed as complexity and precision increased. Cumulative muscle activity, however, increased with these increases in complexity and precision.

Conclusions: This study examined the impact of varying levels of cognitive and precision conditions on muscle activity and kinematics of the trunk and shoulders. Results indicated that increased complexity and precision led to longer lift times and larger cumulative muscle activity, with lower peak muscle activity and velocities. These results suggest that concurrent cognitive load could lead to more muscular fatigue being experienced in manual material handling tasks.

Dedication

Dedicated to my mother

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Fields of Study

Major Field: Industrial and Systems Engineering

Human Factors & Ergonomics

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Chapter 1. Introduction

Musculoskeletal injuries continue to be prevalent in today's working population (Vos et al., 2020). Extensive reviews have examined factors that contribute to work-related musculoskeletal disorders (WMSD) and have identified various exposures that significantly increase injury risk. The National Institute of Occupational Health and Safety (NIOSH) identified several work conditions that resulted in higher risk of developing symptoms including work that involve routine lifting of heavy objects, daily exposure to whole body vibration, routine overhead work, work with chronic neck flexion, and performing repetitive forceful tasks (Bernard, 1997). In many occupations, manual material handling operations include a number of these factors, which is consistent with the high WMSD risks observed in these occupations.

Physical work is seldomly completed in isolation of mental demands. Cognitive loads created by workplace characteristics like attentional requirements or time pressures contribute to the stress experienced by workers which may influence work performance and how individual tasks are completed. A number of studies have examined the effect of a cognitive load on gait and jumping mechanics (Al-Yahya et al., 2011; Almonroeder et al., 2018; Lempke et al., 2021); however, few have studied the effects on material handling tasks similar to those found in occupational settings. In addition, studies that examine cognitive-motor dual-tasking have examined tasks completed serially with a cognitive task preceding the physical task (Davis et al, 2002). The current study focused on the biomechanical loading when physical and cognitive task components are completed simultaneously. The objective of this study was to examine the kinematic and muscle activity changes in the trunk and shoulder that occur during a material handling task given varying levels of cognitive demands, varying task heights, and two levels of task precision requirements.

Specifically, the aims of this study were to:

1. Determine the effects that the addition of a simultaneous cognitive task and increased task precision have on task completion time.
   - Hypothesis: Task completion times will increase for conditions that have both higher precision requirement and higher cognitive demands.
2. Determine the degree to which muscle activity changes in the trunk and shoulder muscles while performing a material handling task, with and without a cognitive dual-task that varies in difficulty and with variations in task precision requirements.
   - Hypothesis: There will be increases in muscle activity with increased cognitive load and precision requirements.
3. Determine the degree to which movement velocities of the torso and arms change as a function of task complexity (cognitive task load and required task precision).
   - Hypothesis: There will be a decrease in torso and arm movement speeds during dual-task conditions
4. Determine the effects of shelf height (3 levels) on the muscle activity and motion parameters across cognitive dual-task and precision conditions.
   - Hypothesis: The effects of cognitive load and task precision are larger when working at non-optimal shelf heights.

Chapter 2. Literature Review

Musculoskeletal disorders and injuries are highly prevalent in the workforce. A systematic analysis on the global burden of 369 diseases and injuries in 204 countries and territories in 2019 found that musculoskeletal disorders were in the top 10 causes of disability-adjusted life-years for people aged 25-49 years (Vos et al., 2020). Low back pain was the 4th highest cause and ‘other musculoskeletal disorders’ were ranked 8th for this age group. The Center for Disease Control and Prevention (CDC) describes musculoskeletal disorders (MSD) as injuries or disorders of the muscles, nerves, tendons, joints, cartilage, or the spinal disks (Center for Disease Prevention and Control, 2020). When the work environment contributes significantly to the condition, worsens the condition, or makes the condition persist longer, the condition is classified as a work-related musculoskeletal disorder (WMSD). The prevalence of these disorders and the severity of their outcomes has prompted safety professionals to study the factors contributing to their development. In 1997, NIOSH released a review of evidence for WMSDs and found that work conditions that involve routine lifting of heavy objects, daily exposure to whole body vibration, routine overhead work, work with the neck in a chronic flexion position, or performing repetitive forceful tasks may lead to development of WMSDs (Bernard, 1997). Another systematic review on the risk factors of WMSD investigated 63 case-controlled longitudinal studies and found that heavy physical work (along with other individual and psycho-social factors) was a major risk factor to WMSD development (da Costa & Vieira, 2009). Similar to NIOSH's findings, this review found that the most reported biomechanical risk factors included excessive repetition, awkward postures, and heavy lifting.

These exposures are especially prevalent in manual material handling work, which is usually characterized by its repetitive and awkwardly postured lifting tasks. Indeed, according to the Canadian Centre for Occupational Health and Safety, manual material handling is the most common cause of occupational fatigue and low back pain. Roughly three of every four Canadians whose job includes manual material handling suffers pain due to back injury at some point (Canadian Centre for Occupational Health and Safety, 2009). A review that examined the prevalence of low back pain across manual material handling workers in the United States, where back pain was defined as seeking medical care due to low back pain and lost time due to low back pain, found that low back pain lasting at least 7 days had a prevalence of 25% (Ferguson et al., 2019). A survey on occupational hazards of manual material handling (MMH) in France also found that MMH workers had a higher exposure to physical hazards and psychosocial factors than the overall group of blue-collar workers, with several of these physical hazards (ex. extreme positions, repetitive motions, vibrations, etc.) being known as risk factors for MSDs (Heran-Le Roy et al., 1999).

A way to represent the development of injury is to describe the workplace parameters, workplace organization parameters, psycho-social parameters, and individual parameters relevant to the workplace. Workplace parameters describe the work and the workspace design. This includes the heights at which the work is performed, the task asymmetry, the lift rate, the reach distances and the level of task repetition. Individual parameters include the anthropometry of the person in relation to their work environment and work style. Workplace organization factors include factors such as the work scheduling, task exposure durations, and work performance incentives. Psychosocial parameters including perceived cognitive demands, job satisfaction, interpersonal interactions with managers and peers, and perceived time pressure are also included as they can influence a worker's attention and motivation. These factors all collectively contribute towards overall work performance and how individual tasks are completed. For example, if a task has a high time pressure and low autonomy due to high managerial oversight, a worker will most likely be under higher stress which has been shown to increase heartrate, blood pressure, and muscle activity (Lundberg et al., 1994). In addition, this worker may focus less on safer lifting behaviors (e.g. be inclined to reach and twist more) to comply with the task's time constraints. The changed nature of the task alters the tissue loads, which in turn influences the risk of developing MSDs.

Describing the cognitive load on a worker adds additional context to the work being done, as physical work is rarely completed in isolation of mental demands and distractions. Cognitive load refers to the effort that is exerted or required while reasoning and thinking. In the context of work, this can refer to the mental effort required to account for work characteristics like time pressures, stresses, and task complexities.

Efforts have been made to describe the connection between cognitive loading and the performance of physical tasks by examining cognitive-motor dual-tasking relationship. Abernethy describes how cognitive-motor interference (CMI) occurs when simultaneous performance of a cognitive task and a motor task negatively affects the performance of one or both of the tasks due to the competing demands of both tasks (Abernethy, 1988). Due to limited processing demands, if the combined tasks exceed a person's total capacity, task performance will deteriorate. To balance these demands, the nervous system will switch attention to the most task-relevant information as it becomes available. However, the attentional switch is not instantaneous. Selecting a response to a stimulus delays, by several hundred milliseconds, the ability to select a response to a second stimulus (known as the psychological refractory period) (Marois & Ivanoff, 2005). These characteristics help contextualize the tradeoff that is seen while dual-tasking, however they do not quantify the performance lost or the changes seen.

Several clinical and experimental studies have attempted to express the relationship between cognitive load and physical movement. Numerous studies have examined the effect of cognitive-motor dual-tasking on gait. A meta-analysis on 66 studies focusing on gait performance while under dual-task conditions identified that dual-task related changes decreased speed, cadence, and stride length and increased stride time and stride time variability (Al-Yahya et al., 2011). A number of studies also examined jumping and landing performance and found that dual-task conditions resulted in higher peak vertical ground reaction forces and lower peak knee flexion angles that resulted in landing mechanics associated with increased ACL loading and decreased jump performance (Almonroeder et al., 2018; Lempke et al., 2021; Dai et al., 2018).

While these studies explore and validate the trade-off associated with cognitive-motor dual-tasking, they have limited relevance to occupational tasks. Few studies have examined these effects on the upper extremity and low back responses. A study by Bank et al. examined this effect by observing the cognitive motor interference effect on a goal-directed upper limb movement task across healthy patients and those with Parkinson’s disease or stroke (Bank et al., 2018). Using the Stroop task (color-word-interference test) as the cognitive task when dual-tasking, the researchers examined patterns of CMI to evaluate overall attentional capacity and allocation. They found that healthy individuals experienced CMI especially under challenging conditions of the motor task and the CMI was greater in participants with Parkinson's. Another study conducted by Srinivasan et al. (2016) compared the heart rate, heart rate variability, and muscle activity of the upper trapezius and extensor carpi radialis muscles across baseline and concurrent cognitive condition during a repetitive pipetting task. The dual-task condition increased trapezius muscle activity by roughly 10% but did not significantly affect extensor carpi radialis activity, heart rate, heart rate variability, or perceived fatigue. A study by Leyman et al. (2004) examined the effect of 3 types of cognitive load (skill-, rule-, and knowledge- based) on a typing task. They observed that the primary task which caused the highest level of perceived workload also produced 61% higher muscle activity in the right trapezius, and 6 and 11% higher activity in the left and right cervical erector spinae in comparison to muscle activity associated with the cognitive task that caused the lowest perceived workload. Villafaina et al. (2019) conducted a study that examined dual-task effects in an arm curl test by examining the number of repetitions when lifting a 2.3 kg weight for women with fibromyalgia and healthy controls. They found a significant decrease in the range of movement in dual-task conditions for both groups when comparing the mean of the first three repetitions with the last three repetitions. Mehta and Agnew (2012) examined the interactive effects of cognitive (arithmetic task) and physical workload on muscle endurance, fatigue, and recovery during intermittent work using intermittent static shoulder abductions to exhaustion at 15, 35, and 55% of individual maximal voluntary contractions. They observed that mental workload was associated with shorter endurance times and greater strength decline, as well as slower heart rate recovery and decreased heart rate variability (indicating increased mental stress). Their results indicated that fatigability and recovery were adversely affected by mental workload. Joseph et al. (2014) examined the influence of precision and cognitive load on upper extremity joint reaction forces, moments, and muscle forces during 30-minute lifting task sessions. They identified that the addition of a precision requirement increased cumulative muscle forces and moments by up to 43% while the addition of cognitive distraction had minimal influence.

Fewer studies have examined dual-tasking's effect on the lower back. Davis et al. studied dual-tasking effects in a study examining serial and simultaneous mental processing task effect on a lifting task (Davis et al., 2002). The findings from that study indicated that simultaneous mental processing had a larger impact on spine loads than the serial task, with the complex condition resulting in increases in lateral shear, anteroposterior shear, and compression compared to all other conditions (simple and complex serial tasks and the simple simultaneous task). Katsuhira et al. (2013) examined the effect of a cognitive-motor dual-task using motion capture to compare the effect of arithmetic on lifting for two different postures: squatting and stooping. Their findings indicated that mental processing significantly increased peak low back compression force and moment, but not lateral flexion moment or rotation moment, for both postures. Norrie et al. (2021) examined the effect of cognitive-motor dual tasking during unexpected spine loading of a 6.8 kg mass. They found that additional cognitive load led to delayed muscle activation responses and greater intersegmental lumbar spine flexion in response to sudden loading.

The variation in the findings of effects due to concurrent cognitive load on physical work could be explained by the large variety of cognitive loading tasks that have been selected across studies. Various studies examined in this review have created a cognitive load using math (counting, subtracting, multiplication), spelling, memory, and auditory-visual inconsistencies to name a few of the employed secondary tasks. Al Yahya et al. (2011) identified 5 distinct categories of cognitive tasks in their systematic review of dual-task effect on gait: reaction time tasks, discrimination and decision-making tasks, mental tracking tasks, working memory tasks, and verbal fluency. Each of these tasks produce different cognitive pressures that may not translate as well when examined across studies. Generally, if a task does not keep the subject mentally occupied during the physical task performance, a smaller effect may be seen. An issue with face validity of the cognitive task arises as well. If a task is not representative of the types of cognitive load that a person realistically experiences in an occupational setting, it can become difficult to translate its effect practically.

The current study attempted to address a gap in the research of cognitive-motor dual-task effect on occupational-representative work by examining a lifting task that represented manual material handling work. Material handling workers are exposed to many cognitive loads while they complete their daily work. While loading and unloading material from pallets to shelves, for example, workers will also need to make dynamic decisions (ex. decide on how to build a pallet optimally), endure work-related and social-related stress (ex. time pressure and managerial pressure), interact with technology (ex. using an inventory tracking/ pallet building system), and track their work task (ex. following procedures and their progress in varying work tasks). These tasks must be done simultaneously with their physical work tasks. This study simulated a common material handling task that had participants cognitively engaged while performing their task to simulate a dynamic work environment. To analyze the interactive cognitive-motor effects, muscle activity and kinematics were tracked with electromyography and motion capture.

Another limitation that a few studies examining the contribution of cognitive loading tasks to biomechanical functionality have is that they have participants complete tasks serially, rather than simultaneously with physical tasks. For example, Davis et al (2002) examined the effect of serial and simultaneous effects of cognitive load on spine biomechanics. For the simple task, participants were verbally given a destination direction (90˚ clockwise or counterclockwise) for a 6.8 and 11.4 kg box. For the complex serial task, participants read an 8-digit serial number off of these boxes which indicated the destination direction. The cognitive and physical tasks were performed serially with one task following the other. This likely described the switching of attention more than the effect of cognitive load. Davis et al. also examined the effect of simultaneous cognitive loading in that same study by having participants place these boxes within the general destination vicinity for the simple condition and within a 1.3 cm tolerance for the complex condition. The simultaneous task used in that study was embedded within the motor task and not a separate cognitive task as was seen in previous studies. Its focus was to increase the precision of the box placement, however a mental processing task was not completed in conjunction with the increased task precision requirement. The study described in this thesis project examined the effects of levels of cognitive load, as well as task precision requirements while the physical task is performed. This study was unique in that it examined the relationship between cognitive dual-task and precision requirements on muscle recruitment during the simultaneous performance of a material handling task. The material handling task simulated a piece-pick replenishment operation frequently performed within distribution centers. The cognitive loading task (time-based math tasks involving subtraction) was completed simultaneously with the material handling task. Variations in the required task precision added an additional layer of cognitive demand by increasing the attention requirements of the task.

Chapter 3. Methods

3.1 Approach

An exploratory laboratory study was conducted to investigate the effects of cognitive load on the biomechanical and kinematic responses to a manual lifting task. This study investigated the effects of three independent variables: (1) the complexity of the added cognitive task, (2) the precision required with regards to load placement, and (3) the destination height at which the box was placed at the completion of the lifting task. Participants were tasked with lifting a 5 kg box off a table, rotating 90˚ to the left, and placing the box at a rack height verbally specified by the primary researcher. In addition to this base assignment, some conditions had math questions that were to be completed simultaneous to this motion (cognitive task conditions), lower lateral clearance on the rack (high precision), or a combination of the two. The complexity of the added cognitive task had 3 levels: complex, simple, and none. There were two levels of the precision requirement (high and low) and there were three levels at which the box was placed (30.5 cm, 91.4 cm, and 152.4 cm), the highest of which corresponded to the 50th percentile US male shoulder height (Attwood et al., 2004). The remaining heights corresponded to approximately waist and knee height. The dependent measures included the electromyographic (EMG) responses from 10 trunk and shoulder muscles and the maximum angular velocities of the shoulders and trunk. The study was approved by The Ohio State University's Institutional Review Board.

3.2 Subjects

Twelve subjects, 11 males and 1 female, were recruited for this study. Inclusion criteria to participate included the subjects being between the ages of 18 and 60, free of any musculoskeletal injury or pain for the prior 6 months, and if female, not pregnant. An additional criterion was that subjects must be able to lift and move a 5 kg box up to 72 times (however this was reduced to 54 lifts). Participants recruited for the study ranged in age from 18 to 27 years old and were all recruited from The Ohio State University Columbus Campus. Subject heights ranged from 169.9 cm to 198.6 cm with a mean of 178.4 cm (SD=8.5 cm). Mean weight of participants was 70.2 kg (SD=9.5 kg). One subject was removed from analysis due to the outlying nature of his data. This participant was not a native English speaker and was translating the numbers for the cognitive task into his native language to complete the math processing then retranslating back to English to respond. This resulted in much longer trial times and an increased and incomparable level of cognitive processing between this subject and the remaining subjects. This subject's data were therefore removed from analysis.

3.3 Experimental Design

Independent Variables

Cognitive Load

An initial pilot study session was conducted to assess the feasibility and performance of the cognitive tasks. In the first session, the simple cognitive task was repeating a phrase stated by the researcher and the complex task was responding verbally to a question posed by the researcher (e.g. “What color do you get when you mix red and yellow”). The rationale behind this form of cognitive tasks stemmed from the observation that the most common distraction experienced in the workforce, while driving, and while performing daily living tasks is talking while performing a task. The pilot tested that concept as a viable cognitive dual-task but found that the answers were too easy and were highly variable such that assessing for correctness could become complicated. A second pilot tested math equations that were based on time calculations to improve task relatability and reliability. Arithmetic testing can easily be administered, can vary in complexity, can easily be assessed for correctness, and has been shown to induce mental stress manifested in increased heart rate and blood pressure (Langewitz & Rüddel, 1989). In the pilot test, a total of 6 variations of time calculations were examined in a quiz format to assess which was the most feasible as a cognitive task. Each variation had 5 simple questions and 5 complex questions with an answer provided for the first question as an example. Examples are provided in **Figures 3.1 and 3.2**. Six participants completed this quiz and then rated the difficulty of each variation of question. An open discussion was conducted after completion of the quiz on the feasibility, improvements, and new potential variations of question format. Variation 5 was considered a preliminary best fit due to its ability to be completed in time with the task and its relative scalability in difficulty.

Variation 1:

<u>Simple</u>: Add 15 minutes to base number

3:00 PM	3:15 PM

<u>Complex</u>: Add 15 mins to base number

4:38 PM	4:53 PM

Variation 2:

<u>Simple</u>: Given time A, determine the amount of time it takes to reach time B

A= 3:10 PM; B= 3:40 PM	30 mins

<u>Complex</u>: Given time A, determine the amount of time it takes to reach time B

A= 4:17 AM; B= 4:32 AM	15 minutes

Variation 3:

<u>Simple</u>: Add a given number to a base time of 3:15 PM

15 minutes	3:30 PM

<u>Complex</u>: Add a given number to a base time of 3:15 PM

9 minutes	3:24 PM

Variation 4:

<u>Simple</u>: Convert minutes to hours and minutes

90 minutes	1 hour and 30 minutes

<u>Complex</u>: Convert minutes to hours and minutes

85 minutes	1 Hour and 25 minutes

Variation 5:

<u>Simple</u>: add the right number of minutes to reach 4:00 PM

3:45 PM	15 minutes

<u>Complex</u>: add the right number of minutes to reach 4:00 PM

3:19 PM	41 minutes

Modified Variation 1:

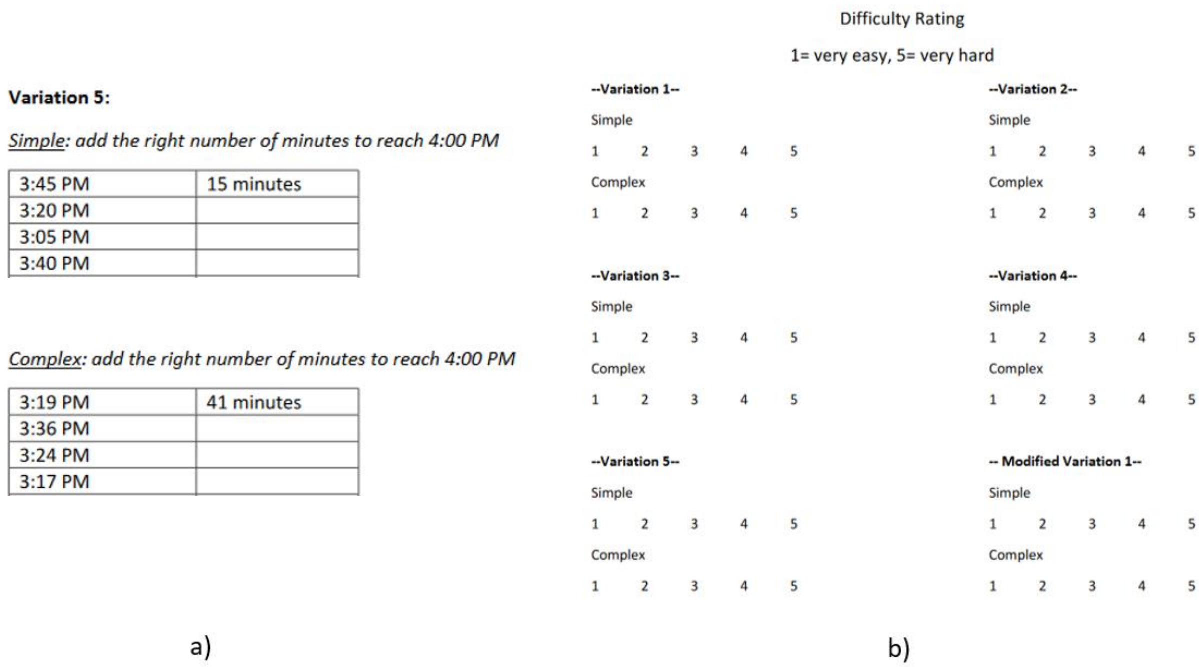
<u>Simple</u>: Add 5 minutes to base number

2:00 PM	2:05 PM

<u>Complex</u>: Add 5 mins to base number

1:38 PM	4:53 PM

Figure 3.1: Example questions from each variation of time-based math task in pilot 2



Variation 5:

Simple: add the right number of minutes to reach 4:00 PM

3:45 PM	15 minutes
3:20 PM	
3:05 PM	
3:40 PM	

Complex: add the right number of minutes to reach 4:00 PM

3:19 PM	41 minutes
3:36 PM	
3:24 PM	
3:17 PM	

a)

Difficulty Rating

1= very easy, 5= very hard

--Variation 1--
Simple
1 2 3 4 5
Complex
1 2 3 4 5

--Variation 2--
Simple
1 2 3 4 5
Complex
1 2 3 4 5

--Variation 3--
Simple
1 2 3 4 5
Complex
1 2 3 4 5

--Variation 4--
Simple
1 2 3 4 5
Complex
1 2 3 4 5

--Variation 5--
Simple
1 2 3 4 5
Complex
1 2 3 4 5

-- Modified Variation 1--
Simple
1 2 3 4 5
Complex
1 2 3 4 5

b)

Figure 3.2: Example questions (left side) and difficulty survey (right side) in Pilot 2

a) Variation 5 questions of the time-based math task. This variation of question was used in the study.

b) The difficulty rating questionnaire provided at the end of the quiz

Upon further testing, the final versions of the cognitive questions were based on pilot variation 5— where the simple task question starts at a random time in multiples of 5 minutes within 3:00-4:00 (e.g. 3:45) and asks the participant to determine how many minutes were needed to get to 4:00 (e.g. 15 minutes). The complex version of the task assigned a random time between 3 and 4:00 (e.g. 3:37) and asked the participant to determine how many minutes were needed to get to 4:10 (e.g. 33 minutes). This was deemed to have the most pronounced effect to differentiate cognitive levels while also being able to be completed feasibly within a reasonable time. Since the physical setup did not require participants to move further than one step, it was necessary to find a complex task that was challenging enough to be engaging while still allowing the task to be completed within a few seconds. The simple condition was under similar restrictions, however it needed a significantly reduced difficulty to represent a lighter cognitive workload. A time-based math task was specifically chosen due to its applicability and face validity in relation to manual material handling work. Workers in MMH fields will often need to make time-related estimations throughout their workday (eg. Estimating the time left for a temporal task or for when their shift changes). To ensure that a cognitive load was present simultaneously with the movement task, a bonus incentive system was created that rewarded fast completion time only when the question was answered correctly. This encouraged participants to complete the cognitive task accurately and the physical task quickly, promoting a synchronized cognitive-motor task. Answers were also only accepted when they were provided after the box was lifted and before it was placed on the rack. This attempted to mitigate the cognitive task being completed in series to the physical task (by either being done before the lifting task or after).

Task Precision

The study investigated two levels of precision: low and high. The low precision constraint did not restrict the lateral clearance within the rack when placing the box at the end of the lifting task. The box that was moved during each lifting task was 45.7 cm wide. The lateral space during low precision conditions was 68.6 cm. The high precision tasks required the box to be placed more precisely by limiting the available placement space within the rack. These trials restricted the lateral clearance by 7 cm on both sides of the rack, resulting in a lateral space during the high precision conditions of 54.6 cm. The vertical dimension of the rack opening, 27.9 cm, was not changed for either precision level. Two foam barriers were taped on either side of each destination rack height for the high precision conditions. Efforts were made to ensure that the barriers did not move when contacted during the trial, using a combination of tape and a close fit between the rack beam and the barrier.

Destination Height

Three levels of destination height, categorized as high, middle, and low, were 152.4 cm, 91.4 cm, and 30.5 cm from the ground, respectively. They corresponded to roughly shoulder, waist, and knee height and represented different placement heights that are prevalent in work settings.

Dependent Variables

Electromyography

The dependent variables in the study included muscle activity levels and back and shoulder kinematics. The muscle activity levels were measured using surface electromyography (EMG). Electrodes were placed bilaterally over the right and left latissimus dorsi, erector spinae, internal oblique, external oblique, rectus abdominus, and anterior deltoid muscles. The 90^{th} percentile normalized EMG values were extracted from each trial and analyzed across conditions. These 90th percentile values were analyzed for only the second half of each trial to focus on the placement task. They represent peak muscle activity. A random sampling of trials verified that the halfway point corresponded to roughly the end of the twisting motion before the placement task. Focusing solely on the 2nd half of the analysis was deemed appropriate as the initial lifting portion of the task did not differ greatly across task conditions and did not provide relevant data to the analysis. In addition to the 90th percentile values, integrated values were also extracted by summing the normalized muscle activity for each frame (where the frame rate was 1000 frames per second). For the integrated analysis, the complete trial was analyzed to determine the cumulative muscle activity for the duration of the activity.

Kinematics

Kinematic motion was measured using the 3D Motion Monitor System (Innovative Sports, Chicago). The Motion Monitor software provides researchers with body segment orientation along with segment velocities. Motion capture sensors (Ascension Flock of Birds) were placed on the upper arms, torso (T1 level), head, and pelvis (S1 level). Data that were extracted and analyzed from the Motion Monitor software were trunk and shoulder velocities. For analysis, the maximum velocities were compared across conditions. Initially, maximum joint angles were examined across conditions, however velocities proved to be the more relevant measure. Since the lifting task for each destination heights were the same across conditions, position data did not differ significantly across conditions, cognitive load or precision. These position metrics were driven more by the height differences than the other conditions and therefore were not sensitive to changes in cognitive demands. Angular velocities, on the other hand, appeared to be more sensitive to variations in cognitive load and task precision requirements.

The measures that were examined were the segment velocities of the trunk and shoulders. In particular, the velocities examined were trunk flexion and extension, trunk twisting (mainly examining the left-side twist as this was the primary motion), trunk lateral bend (measured in terms of maximum velocity from either left or right), and shoulder flexion and extension. These measures were analyzed in two distinct phases— manually selected for each motion trial. The first phase captured the initial lifting of the box and the completion of the left twist. The second phase captured the placement of the box at the designated rack location.

Completion Time

Two other variables tracked were the trial completion time and the subjective difficulty of each cognitive task question. These were primarily used to validate the task complexity conditions. In addition, the trial completion time was used to determine part of the bonus incentive that was based on the speed with which participants completed the trial. Time differences between conditions were also considered as a measure of cognitive load. The time used for performance payout was recorded using a stopwatch. The trial time record began when the researcher stated the last phrase of the prompt for the subject (either a height or question depending on the condition block) and ended when the box left the hand of the subject after being placed on the rack. This method of tracking time was only used to record time for incentive calculations. Time measurements used for statistical processing were determined by trimming the file based on anterior deltoid activity, as described in **section 3.7**.

Subjective Difficulty

The subjective difficulty for each of the task questions was collected at the end of each trial by recording the response to the prompt: “What would you rate the difficulty of the math task independent of the physical task on a scale of 1-10 with 10 being the highest difficulty”. This rating was collected to verify that the question difficulty across the simple and complex conditions were significantly different and therefore indicated a clear increased difficulty of the more challenging questions compared to the simple questions.

3.5 Apparatus

A simulated warehouse rack was created using a Creform ® pipe frame (Creform.com). The high destination height was set 152.4 cm above the floor, the middle destination height was 91.4 cm above the floor, and the low destination height was 30.5 cm above the floor. For high precision tasks, two rectangular pieces of foam were taped on either end of the rack location to reduce the lateral clearance. During the high precision tasks, lateral space was 54.6 cm. Given the box was 45.7 cm wide, this restricted the excess space to 8.9 cm. In the low precision conditions, the excess space was 22.9 cm. The depth of the rack was not pertinent to the physical task because the participants were instructed to release the box onto tracks embedded in the rack to let the box slide into place. **Figure 3.3** shows both the low and high precision rack setup. Paper was taped between unused racks to reduce placement errors. At the beginning of each trial, the box started on a table that was adjusted to the participant’s knuckle height. The table was marked so that the box was consistently placed in the same spot. For each trial, a participant grabbed the box off the table, turned 90˚ to their left side, and placed the box in the rack at the level verbally indicated by the researcher. Feet movement was not restricted during trials. The box had the following dimensions and was consistent throughout every trial: width- 45.7 cm, height- 17.8 cm, and depth- 29.2 cm. The box weighed 5 kgs. For every trial, the box was placed in the rack with the 45.7 cm side facing the participants. Examples of the placement task can be found in the following procedure section.

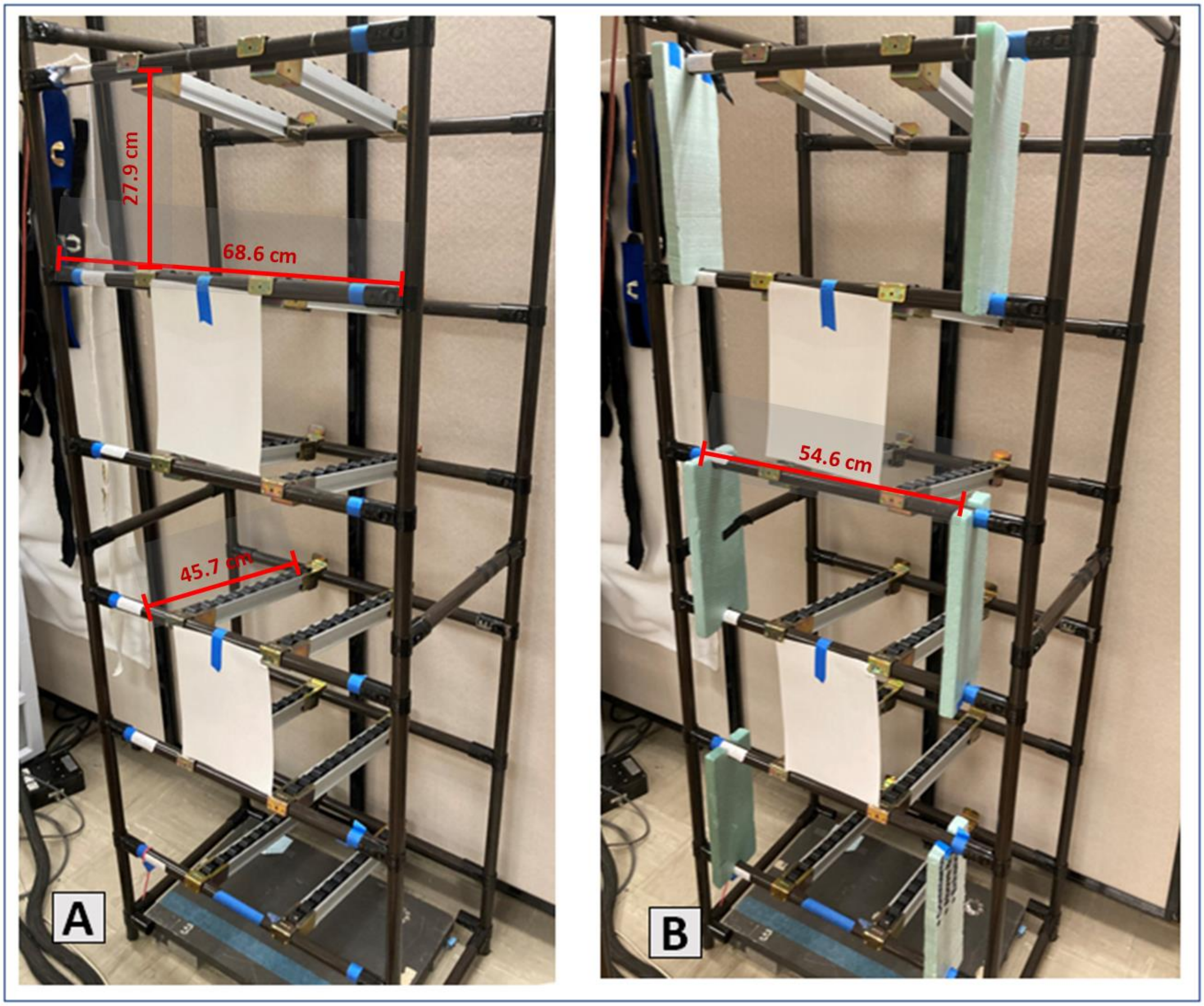


Figure 3.3 Rack setup for (A) Low precision and (B) High Precision Conditions.

3.6 Procedure

Upon arrival, participants were informed about the study and provided a consent document describing the activities, compensation, and any risks that could arise while involved in the study. After the participant provided informed consent, their height, weight, and age were recorded. To prepare for EMG electrode placement, the areas of skin where sensors would be placed were shaved (if necessary) and cleaned with rubbing alcohol. Surface EMG electrodes were then placed bilaterally according to methods proposed by Mirka & Marras (1993) over the right and left latissimus dorsi at approximately the T9 level and oriented on a line between the lateral edge of the axilla and the sacrum, erector spinae at the L3 level approximately 3 cm lateral to the spine process, external oblique electrodes were placed halfway between the ribcage and the anterior superior iliac spine approximately 12 cm from midline, rectus abdominus bilaterally approximately 2.5 cm lateral to the umbilicus, and anterior deltoid muscles approximately halfway between the most superior aspect of the shoulder and the distal end of the deltoid muscle. All electrodes were attached to the skin using Tegaderm Transparent Film Roll (3M, Maplewood, MN).

Following the electrode placement, a set of maximal voluntary exertions was performed for EMG normalization using a static strength tester. For each muscle pair (aside from the rectus abdominus and external oblique which were combined to one maximum exertion), maximum exertion trials were completed through isometric exertions designed to extract representative maximum values while in body postures where the highest exertions would be expected for the corresponding muscles. Each maximum exertion was completed twice with a one-to-two-minute rest period between exertions. **Figure 3.4** shows these maximum exertion trials.

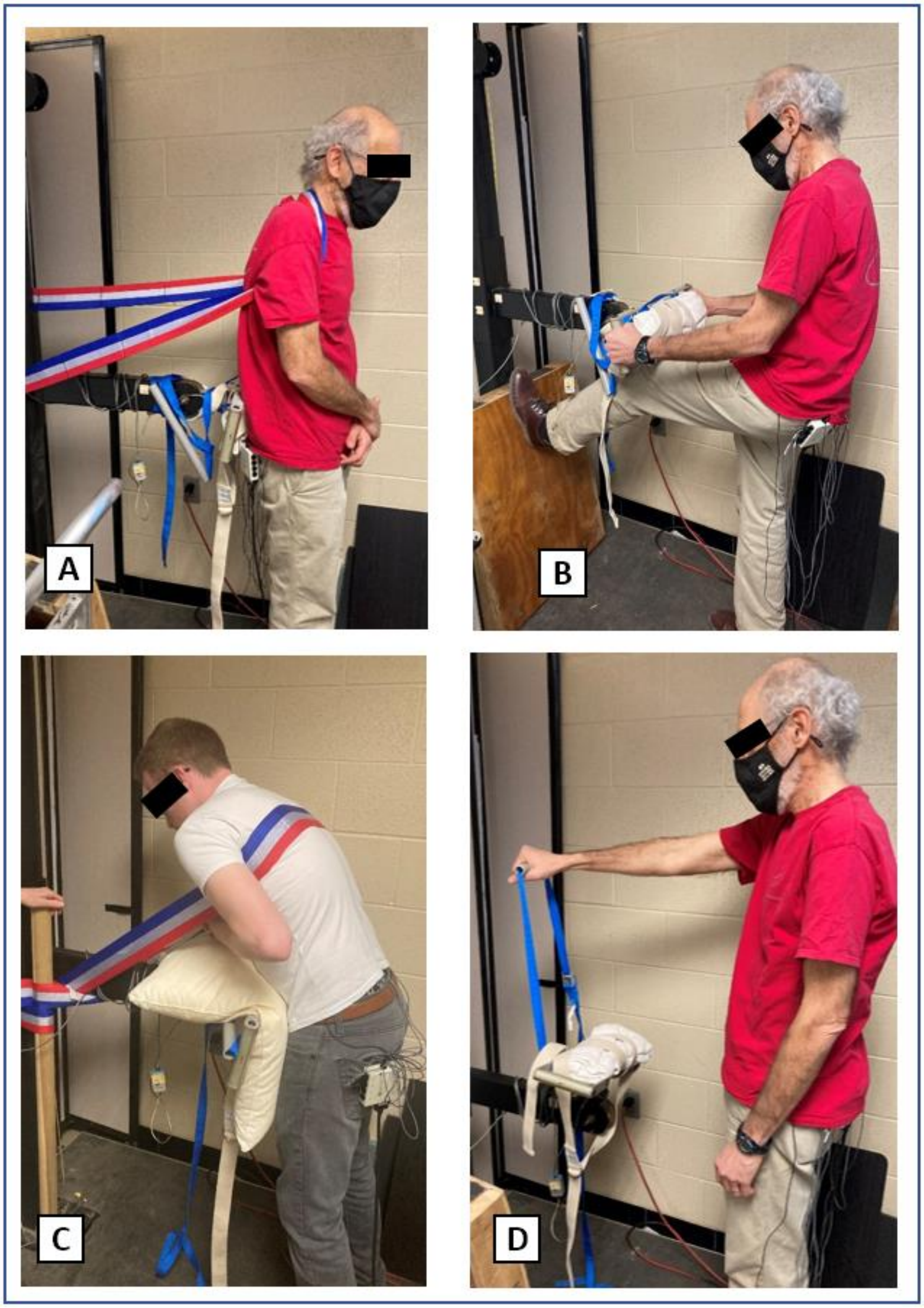


Figure 3.4 Maximum exertion trial setup to collect electromyographic data from (A) Rectus Abdominus and External Obliques (B) Latissimus Dorsi (C) Erector Spinae and (D) Anterior Deltoids.

Following these exertions, motion capture sensors were strapped on the participant to obtain the shoulder and torso kinematic data. These sensors were attached using Velcro straps and were attached to the upper arm, the upper forearm, the upper back, the sacrum, and the head. A 3D biomechanical model was then generated by these sensors and calibrated by having the participant stand in the neutral posture.

Once the participant was instrumented with EMG electrodes and motion capture sensors, a short training session on the task was initiated. Participants were given a sample of 3-4 trials from each of the cognitive conditions (no cognitive load, simple load, and complex load) and were given an opportunity to practice them so that they understood the tasks and data collection process. Participants were also all provided with the same example approach to completing the math task and were encouraged to use whatever method worked for them. Once participants felt comfortable with each of the cognitive tasks, the data collection process was initiated.

The participants started each trial with the rack to their left and the table with the 5 kg box located in front of them. The starting precision level (high/low) was randomized for each subject. Once a precision level was set, the subject completed all the conditions under that precision level before moving to the next level. Within precision level, the order of the three cognitive condition levels was randomized. Once a cognitive condition level was complete, the next randomly selected one began. Lastly, the three destination heights within each cognitive condition level were also completed in a randomized sequence for each participant within each cognitive condition. **Figure 3.5** lists the trial breakdown. Three lifts were completed for each rack height and cognitive*precision condition combination.

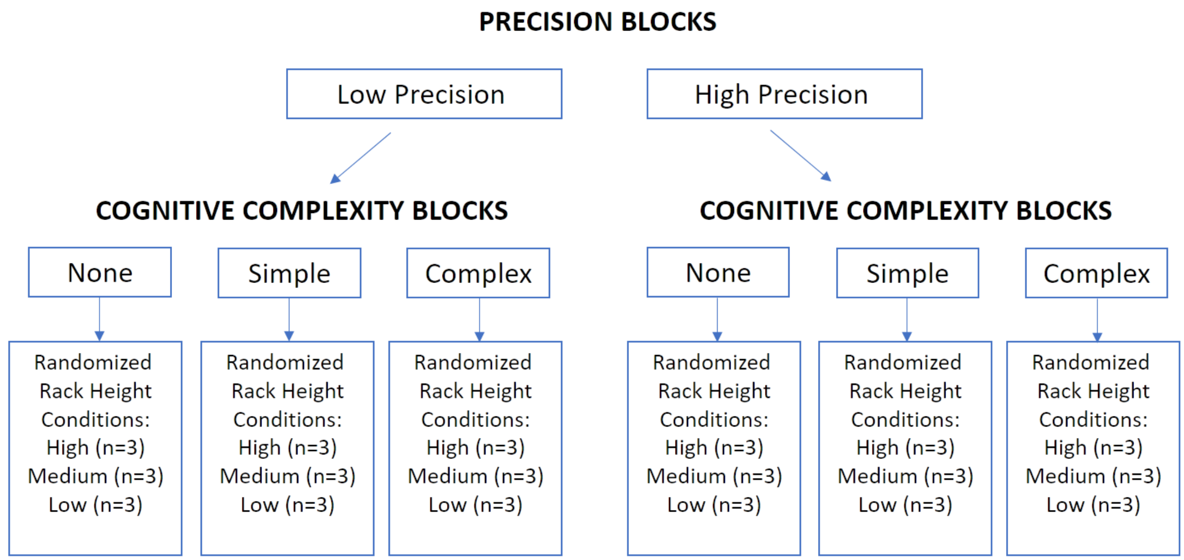


Figure 3.5: Lift condition as a function of precision, cognitive load, and rack height

Each trial was initiated by the researcher telling the participant the height of the destination (in the no cognitive load condition), or by telling the participant the height and the math problem. The participant then lifted the box off the table and placed it on the rack at the height specified by the researcher. In all conditions, the participants were instructed to start off in the neutral position at the beginning of the trial and then immediately move the box to the specified rack height. Participants were encouraged to complete the trial as quickly and accurately as possible using the incentive system described below. A secondary researcher started a stopwatch right after the primary researcher specified the height in the no cognitive load conditions or the height and the math problem in the cognitive load conditions and stopped the stopwatch once the participant let go of the box after placing it on the rack.

For the first few trials in each cognitive load condition block, the participant was reminded what their goal time for the math problem was (either 4:00 for simple cognitive load or 4:10 for complex cognitive load). Participants were informed that they could not provide an answer before picking up the box off the cart or after placing the box on the rack. This was to ensure that the cognitive processing was done within the motion task. **Figure 3.6** shows an example of the physical task for each height for the high precision trials.

This process was completed for each of the 6 Precision-Complexity condition blocks. Individual lifts were separated by approximately 45-60 seconds. After each condition block (6 total), there was approximately 120 seconds of rest for each participant. Participants were also given a stool to sit on while the precision conditions were changed.

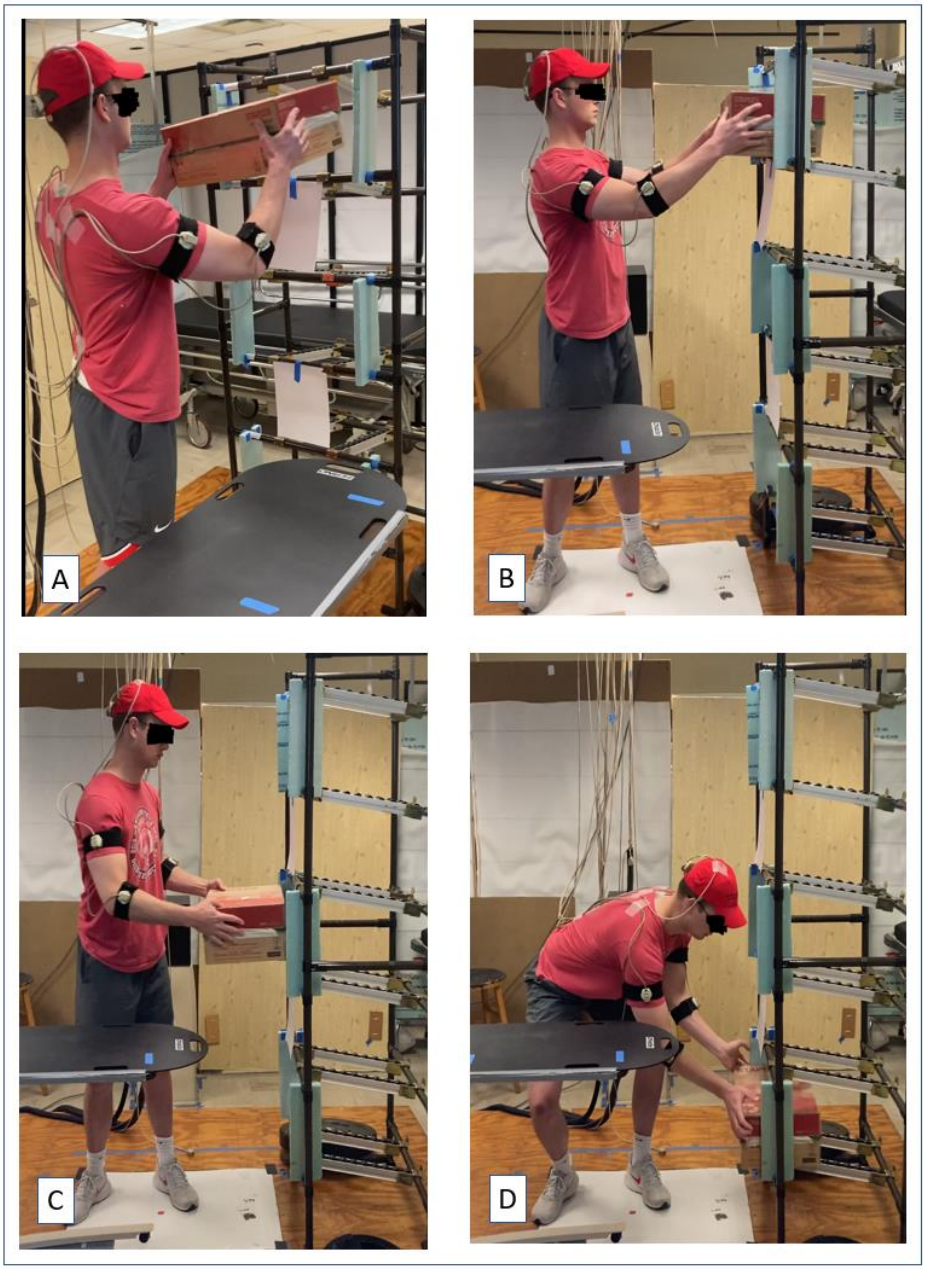


Figure 3.6 Physical task for high precision conditions for each rack height: (A) High height: diagonal view (B) High height: side view (C) Middle height: side view (D) Low height: side view

Incentive

A 30-dollar base participation incentive was paid to each participant. An additional bonus incentive based on performance allowed participants an opportunity to earn \$0.40 for each correct and timely answer to the 36 simple and complex cognitive questions resulting in a total potential bonus of \$14.40. The payoff matrix for this incentive is provided in **Table 3.1**. A participant did not earn a bonus for incorrect answers, however they earned between \$0.15-\$0.40 for each correct answer depending on the time taken to complete the lifting task. If the box was moved in four seconds or less to the correct location and the cognitive task question was answered correctly, the participant earned an additional \$0.40 for that trial. If the lifting task took between 4 and 7 seconds, the participant earned an additional \$0.20 for the lift, and if the participant took greater than 7 seconds to move the box, they earned \$0.15. The researchers estimated the time to answer the questions as roughly 1-2 seconds. Without the cognitive load, the lifting task could easily be completed in the same time. Therefore, a grace period of 4 seconds for the simultaneous task was deemed appropriate. The time and accuracy pressure created by this incentive system resulted in participants completing the cognitive and physical task simultaneously.

Table 3.1: Bonus Incentive Breakdown for Simple and Complex Cognitive Load Conditions

For each answer		
time:	**incorrect**	**correct**
t =< 4	0	\$ 0.40
4< t <=7	0	\$ 0.20
t > 7	0	\$ 0.15

3.7 Data Processing

The analog EMG data were sampled through the Motion Monitor data acquisition system (Innsport, Chicago, IL) at 2000 Hz. The raw data were band pass filtered between 20 and 500 Hz, and notch filters were applied at 60, 120, 180, 240, 300, 360, 420, and 480 Hz. The motion capture data were synchronously captured at 100 Hz with a 6 Hz Butterworth filter smoothing function. EMG data were collected using a Trigno wireless system with single differential surface electrodes (Delsys, Natick, MA).

The data collected during the study were processed using MATLAB (Mathworks, Boston MA). Raw EMG data were recorded at 2000 frames per second (2000 Hz) and then RMS processed in the MotionMonitor system with a 100ms time constant prior to being exported. A custom script written in MATLAB normalized EMG data, removed artifacts, and allowed for trimming of trials. The EMG trial data were normalized by calculating the activity level as a percentage of the maximum voluntary contraction (%MVC) values for each muscle. This was done by subtracting each trial's data point by the minimum value of the resting trial for the relative muscle, and then dividing this number by the maximum effort for a given muscle (determined as the largest maximum exertion value across all maximum exertion trials) subtracting the minimum value from the resting trial. This number was then multiplied by 100.

The 90th percentile and integrated values for each trial were then extracted from the normalized data. The 90th percentile values were analyzed for only the second half of each trial. This analysis was completed by dividing the trimmed trial file in half and analyzing the second portion. The integrated values were analyzed by summing the normalized muscle activity for each frame for the duration of the trimmed trial file.

EMG trials were trimmed using the MATLAB script with the activity in the right anterior deltoid used as an indicator of start and end times. Initial activity in the anterior deltoid proved to be a reliable marker of when the participant reached for the box off on the table and the sudden drop of activity in the anterior deltoid muscle also indicates the end of the trial due to the box getting placed on the shelf and the subsequent dropping of the shoulders at the end of the task**.** An example of this is provided in **Figure 3.6** below. Artifacts were also trimmed by having the user select start and end points to ensure artifact values were not included.

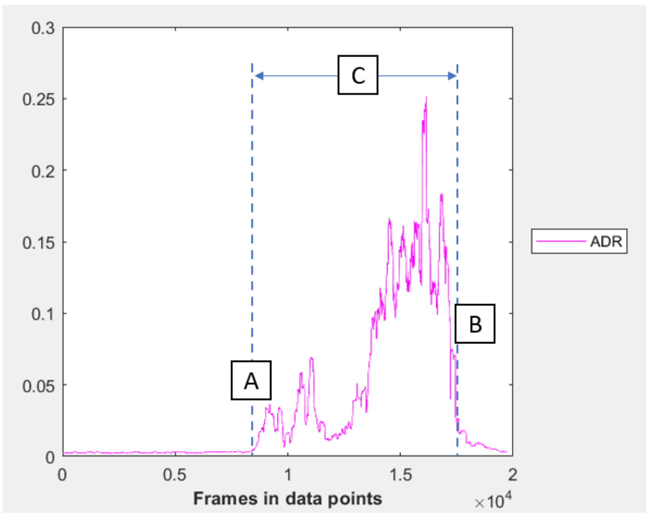


Figure 3.7 Example anterior deltoid file used to determine trial start and end times: (A) trial start selection point, (B) trial end selection point, and (C) trial duration

Segment velocities were analyzed using MATLAB, which was used to trim each trial into two phases: the beginning of the trial to the manually selected frame after the left twist was completed, and from the end of the left twist to the end of the trial. The first phase captured the initial lift and subsequent left twist. Maximum velocities for each of the measurements were then extracted for statistical analysis. The first phase examined all the heights as a factor in the analysis. The values of the initial lift of the box off the cart did not differ based on the height assigned. Therefore, the data were pooled across destination heights. The second phase analyzed the effects of cognitive load and precision separately for each destination height. The destination height greatly influenced the motion that would be seen in the second half since, depending on the destination height, different motions were used that would mask the observable effects of cognitive load and precision. The end of the twist to the left was selected as the phase transition point for two reasons: first, it provided a clear landmark across trials; second, it also allowed the two main relevant motions to be described separately—the twist in the first phase and the placement in the second phase. Therefore, an analysis was done to separately describe the effects. The twist was also deemed appropriate to be captured in the first phase as it was not influenced by the destination height.

Some measures were not examined for both the first and second phases. For example, the right trunk twist was not examined in the first phase as the primary and relevant motion was the left trunk twist. The left and right shoulder extensions were not examined in the second phase as the primary and relevant motion was the shoulder flexion as the box was placed in the rack. The trunk lateral bend was analyzed as the maximum velocity from either direction (left or right) as this movement was generally based on the subject's personal preference/movement style. Thus, it was the velocity of the bend that was important to characterize, not the direction.

3.8 Data Analysis

Data Processing

An issue that developed when processing the data of some subjects was that of embedded artifacts blending with the normal muscle activity signals. Before processing, signal artifacts (usually characterized by abnormal and extreme spikes of activity) were removed with a MATLAB program that enabled its user to manually select and remove artifacts. Careful consideration ensured that artifacts were not removed to intentionally misrepresent the data. After this initial correction and subsequent processing, an issue was identified where a select number of subjects had excessive and unrealistic muscle activity levels while still having signals that did not seem to have obvious artifacts (ex. having a normalized 90th percentile anterior deltoid value of 85% MVC). The cause was theorized as a symptom of motion artifacts created by rapid movement during the trials which lead to subtle shaking of the EMG electrodes which reduced the contact with the skin. Tests replicating this subtle shaking movement observed similar effects. To account for these embedded artifacts, the resulting 90th percentile values for muscles were filtered with the following condition: the 90th percentile muscle value for a subject was excluded from the statistical analysis if the value was both above 70% MVC and larger than the sum of the subject's mean of that muscle plus 2 standard deviations. Using this approach, 78 out of 11,586 values were excluded due to this filtering process.

Statistical Analysis

One-way, two-way, and three-way ANOVAs, blocked on subjects, were performed using Proc GLM within SAS 9.4 (SAS Institute; Cary, NC) to compare the main effects of cognitive workload and placement precision on trunk and shoulder muscle activities and angular segment velocities, task completion time, and subjective difficulty. Interaction effects between complexity, precision, and rack height were also examined. Proc GLM was used for post hoc testing with Bonferroni correction to evaluate the two- and three-way interactions.

Chapter 4. Results

4.1 Overview

The analysis of task duration and perceived task difficulty will be presented first, given these measures can be viewed as protocol validation indicators. This section is then followed by results from the cognitive workload main effect, described first in terms of its effect on kinematics through an analysis of the maximum velocities, and then on muscle activity through an analysis of the 90^{th} percentile and integrated normalized muscle activity values. This process was repeated for the precision main effect and then subsequent interaction effects of complexity*precision, complexity*height, precision*height as applicable. The complexity*precision*height interaction analysis was not included since this interaction was not significant for any of the measures. In these analyses, destination shelf height has shown significant main effects for the majority of variables; however, the effects of shelf height will not be focused on in this description of the results given that one would clearly expect different movements and muscle activations as a function of shelf height. Significance tables identifying which measures had significant main and interaction effects are provided in **Section 4.3.** For each of the significance tables, the green highlighted cells signify that a significant effect was seen for that measure. The p-value is also listed in the cells. The cells highlighted in yellow indicate measures that showed borderline significance ($0.05<p<0.07$). Any cell that had 'NS' signifies that the effect was not statistically significant for that measure.

4.2 Protocol Validation Measures

This first subsection examined the complexity effects for completion time and question difficulty. **Table 4.1** shows the significant effects for completion time and perceived question difficulty. For the task completion times, significant main effects were found for each independent variable, as well as a significant precision*height interactions effect.

Table 4.1: P-values for Completion Time and Subjective Difficulty Main and Interaction Effects

Significance Table- Time and Difficulty							
Measure	Complexity	Precision	Height	C*H	P*H	C*P	C*P*H
Completion Time	<0.001	0.0018	0.0007	NS	0.004	NS	NS
Question Difficulty	<0.001	NS	NS	NS	0.0596	0.0313	NS

Completion Time

A significant difference for each cognitive load level was observed for completion time. The Complex conditions resulted in the longest average trial time (μ=3.02 seconds SE=0.096), followed by the Simple conditions (μ=2.23 seconds SE=0.063), and the None conditions with the shortest average time (μ=2.00 seconds SE=0.063). **Figure 4.1** plotted the significant main and interaction effects observed for completion time. **Figure 4.1A** shows main effect for cognitive load complexity. Relative to the condition with no cognitive task, the simple task, on average increased task duration by 0.23 seconds, and the complex task increased the task duration by 1.02 seconds. As for precision, **Figure 4.1B** shows that the conditions with the low precision constraints (μ=2.21 seconds SE=0.068) took significantly less time to complete than those with high precision constraints (μ=2.61 seconds SE=0.074). Placing box at the lower height led to longer task durations (**Figure 4.1C**), however there were no differences between the middle or high conditions. The precision by height interaction, after the Bonferroni adjustment (0.05/3) was made to the alpha level, shows significantly longer task durations at the low and middle heights for the high precision condition (**Figure 4.1D**). For the Low height, the High Precision condition increased the completion time by 0.60 seconds. For the Middle height, task durations increased for the High Precision by 0.31 seconds. A non-significant but similar trend was observed in the High height condition.

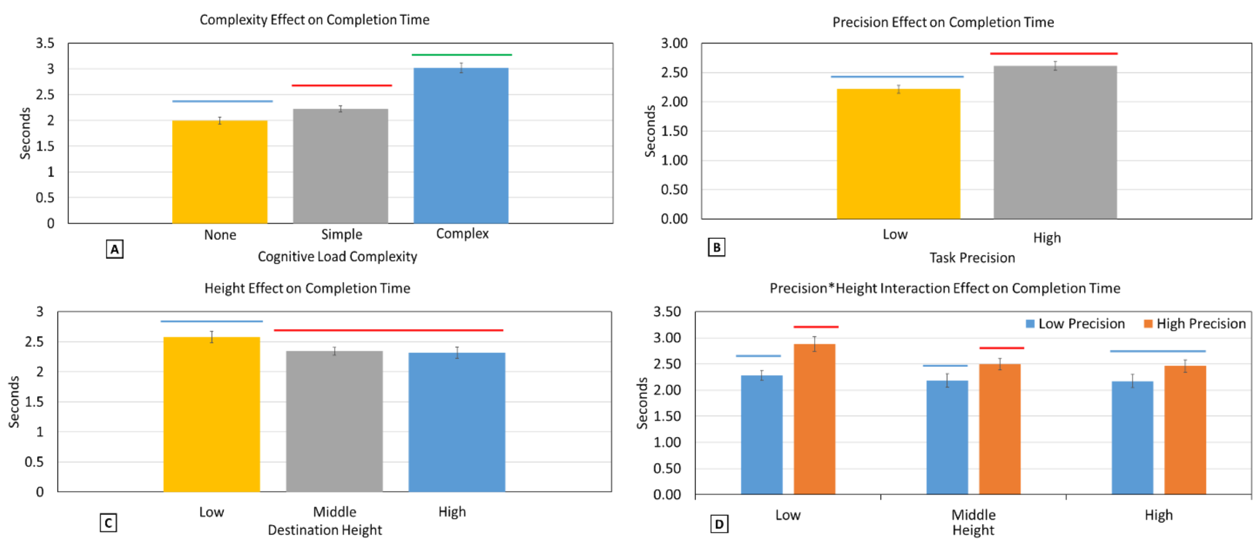


Figure 4.1: Significant Effects on Completion Time by Effect: (A) Cognitive load (B) Precision (C) Height and (D) Precision*Height. Horizontal bars that have different colors and positions between conditions represent statistically significant differences.

Question Difficulty

Significant effects for perception of question difficulty were found for cognitive workload, and the cognitive workload*precision interactions (**Table 4.1**). A cognitive workload effect was observed and was plotted in **Figure 4.2A** below, showing the significant interaction effects. The Complex conditions (μ=4.94 rating SE=0.182) had a significantly larger difficulty rating than the Simple conditions (μ=2.54 rating SE=0.127). These ratings were on a 10-point scale with 10 being the most difficult.

The significant cognitive load complexity and task precision interaction is shown in **Figure 4.2B.** After a Bonferroni adjustment for the multiple comparisons, a significant effect between the Low and High Precision levels was seen for the Simple condition (μ=1.95 rating SE=0.059 and μ=2.50 rating SE=0.089 respectively). There was no statistically significant difference between the precision levels for the Complex conditions (low precision: μ=2.87 rating SE=0.121; high precision: μ=3.17 rating SE=0.147).

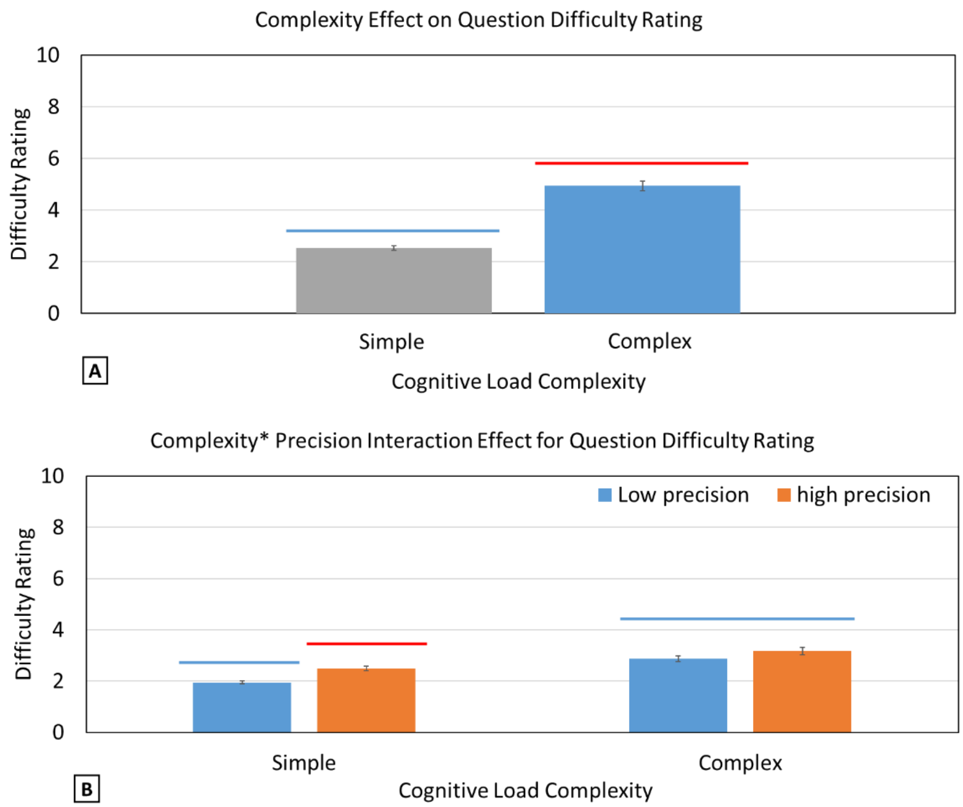


Figure 4.2 Significant Effects on Subjective Question Difficulty Rating by effect: (A) Cognitive load and (B) Cognitive workload *Precision. Horizontal bars that have different colors and positions between conditions represent statistically significant differences.

4.3 Cognitive Workload Main Effect

Kinematics

Phase 1

The cognitive workload effect was examined for the first phase of the kinematics analysis. This phase comprised the initial lift and left twist. A table providing the significant main and interaction effects of cognitive load complexity, task precision, and destination height on angular velocity is provided in **Table 4.2** for this first phase. **Table A.1** in **Appendix A** listed definitions of the abbreviations for kinematic measures used in the analysis. Significant main effects of cognitive load complexity and destination height were determined through the statistical analysis; however, the task precision effect was not significant during this initial lifting phase. The significant cognitive workload main effects were found for the Trunk Flexion, Left Trunk Twist, Left Shoulder Flexion, Left Shoulder Extension, and Right Shoulder Flexion. Interaction effects of cognitive workload *height, precision*height, and cognitive workload *precision were also observed for some measures and are provided in the table below.

Table 4.2: P-values for (Phase 1) Angular Velocity Main and Interaction Effects

Significance Table- Angular Velocities (Phase 1)							
Segment	**Complexity**	**Precision**	**Height**	**C*H**	**P*H**	**C*P**	**C*P*H**
trunkFlexP1	<0.001	NS	0.0266	NS	NS	0.0204	NS
trunkExtP1	NS	NS	<0.001	<0.001	NS	NS	NS
LtrunkTwistP1	<0.001	NS	0.0277	NS	NS	0.056	NS
trunkLatBendP1	0.0626	NS	0.001	0.0077	NS	NS	NS
LShFlexP1	<0.001	NS	0.0034	NS	NS	0.0053	NS
LShExtP1	<0.001	NS	<0.001	0.0332	0.025	NS	NS
RShFlexP1	<0.001	NS	0.0387	NS	NS	0.035	NS
RShExtP1	NS	NS	<0.001	0.0133	0.0104	NS	NS

Figure 4.3 A and B show the angular velocities that had significant changes due to task complexity for the trunk and shoulder, respectively. The measured velocities for Trunk Flexion, Left Trunk Twist, Left Shoulder Flexion, Left Shoulder Extension, and Right Shoulder Flexion all were significantly larger for the None (no added cognitive workload) conditions than those seen during the Simple and Complex conditions. The complexity main effects observed were also influenced by both precision (Trunk Flexion, Left Trunk Twist, Left Shoulder Flexion, and Right Shoulder Flexion) and height (Trunk Extension, Trunk Lateral Bend, and Left Shoulder

Extension) as described in **Section 4.5** and **Section 4.6** respectively. **Table B.1** in **Appendix B** provides the angular velocity mean and changes across cognitive workload conditions for phase 1 and phase 2 angular velocity measures.

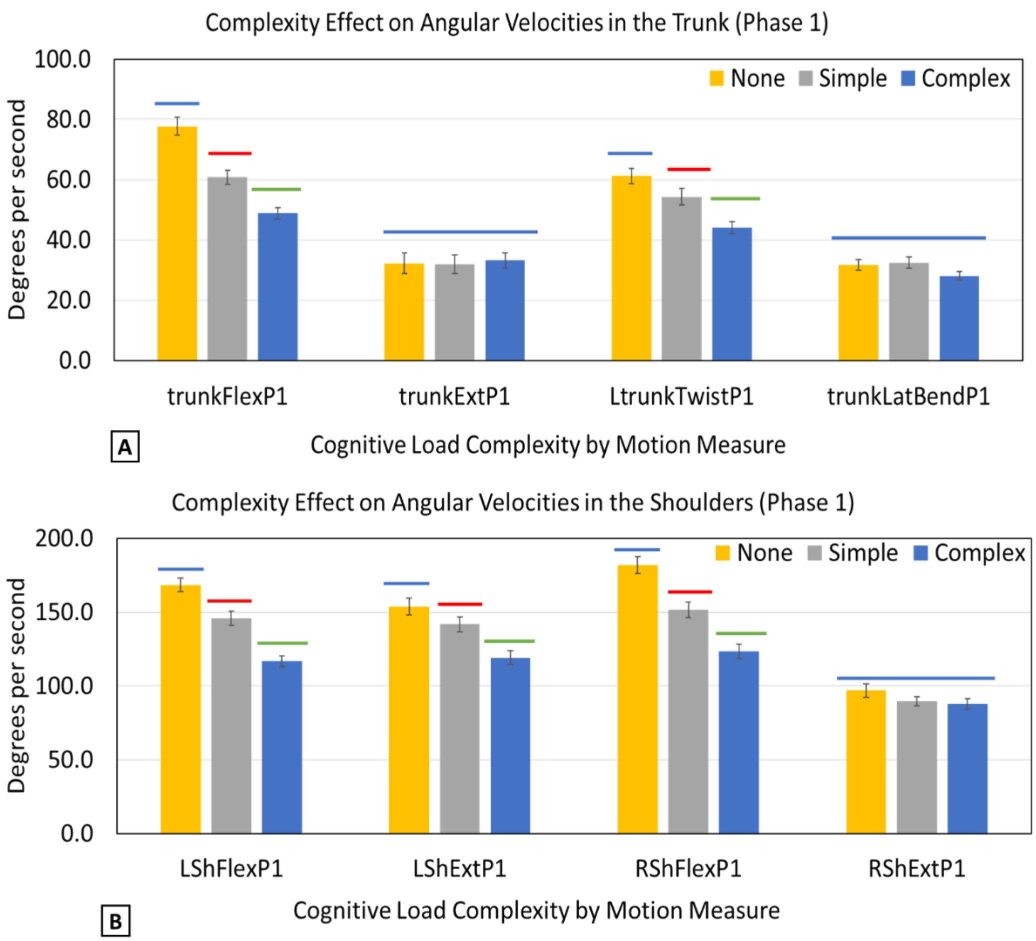


Figure 4.3: Cognitive workload effect for kinematic measures in Phase 1 for the (A) Trunk and (B) Shoulders. Horizontal bars that have different colors and positions between conditions indicate statistically significant differences.

Phase 2

Table 4.3 shows main and interaction effects for the second phase of the kinematic analysis where the box was placed on the shelves. For this analysis, the effects of cognitive load and task precision were examined separately for the three destination height levels. For the different heights, a mixture of cognitive load and precision main effects were found to be significant. For the high destination height, nearly all measures showed cognitive load main effects, while only one precision effect for the Left Trunk Twist was identified. As shown in **Figure 4.4A**, for each significant effect, the No added cognitive load conditions had the highest angular velocity, followed by the Simple and Complex conditions. For Trunk Extension, the None and Simple conditions were not significantly different however were significantly larger than the Complex conditions. Similar trends were seen for the Left and Right Shoulder Flexion. Left Trunk Twist had a significantly larger angular velocity for the None conditions than the Simple and Complex conditions (which did not differ significantly). A similar trend was seen for the Trunk Lateral Bend.

At the middle destination height, significant cognitive workload effects were found for the Trunk Flexion, Trunk Extension, and Left Trunk Twist velocities. In addition, precision effects were identified for both Left and Right Shoulder Flexion velocities. **Figure 4.4B** shows the cognitive workload effect on angular velocity for the middle destination height in phase 2. The Trunk Flexion velocities, while very low overall, were not different between the None and Simple conditions, however both of these conditions were statistically lower than the Complex cognitive conditions. For Trunk Extension, the None conditions had significantly higher angular velocity compared to the Complex conditions. The None and Simple conditions and the Simple and Complex conditions did not have statistically significant differences. The Left Trunk Twist had a statistically significant lower angular velocity for the Complex conditions compared to the None and Simple conditions, which were not significantly different.

For the low height, significant cognitive workload effects were observed for Trunk Flexion, Right Trunk Twist, and Trunk Lateral Bend velocities. For the precision main effect, significant effects were observed for Trunk Lateral Bend and Left and Right Shoulder Flexion velocities. While a significant main cognitive load effect was not observed at this low destination height, there was a significant cognitive workload*precision effect for the Right Shoulder Flexion velocity for both Low and High Precision as described in **Section 4.5**. **Figure 4.4C** shows that while the Trunk Flexion velocities were not different across the None and Simple conditions, they both were significantly lower than the Trunk Flexion velocity in the Complex conditions. For the Right Trunk Twist, the None conditions had a significantly larger angular velocity than both the Simple and Complex conditions, which did not statistically differ between each other. For the Trunk Lateral Bend velocities, the None conditions had significantly higher values than the Complex conditions. The None and Simple conditions and the Simple and Complex conditions did not have statistically significant differences.

Table 4.3: P-values for (Phase 2) Angular Velocity Main and Interaction Effects

Significance Table- Angular Velocity (Phase 2)			
Height	**High**		
Segment	**Complexity**	**Precision**	**C*P**
trunkFlexP2	NS	NS	NS
trunkExtP2	<0.001	NS	NS
LtrunkTwistP2	<0.001	0.0158	NS
RtrunkTwistP2	NS	NS	NS
trunkLatBendP2	0.0065	NS	NS
LShFlexP2	<0.001	NS	NS
RShFlexP2	<0.001	NS	NS
Height	**Middle**		
Segment	**Complexity**	**Precision**	**C*P**
trunkFlexP2	0.0104	NS	NS
trunkExtP2	0.0114	NS	NS
LtrunkTwistP2	0.0012	<0.001	NS
RtrunkTwistP2	NS	NS	NS
trunkLatBendP2	NS	NS	NS
LShFlexP2	0.0684	<0.001	NS
RShFlexP2	NS	0.0109	NS
Height	**Low**		
Segment	**Complexity**	**Precision**	**C*P**
trunkFlexP2	0.0034	NS	NS
trunkExtP2	NS	NS	NS
LtrunkTwistP2	NS	NS	NS
RtrunkTwistP2	0.008	NS	NS
trunkLatBendP2	0.003	0.0108	NS
LShFlexP2	NS	0.0155	NS
RShFlexP2	NS	0.015	0.0453

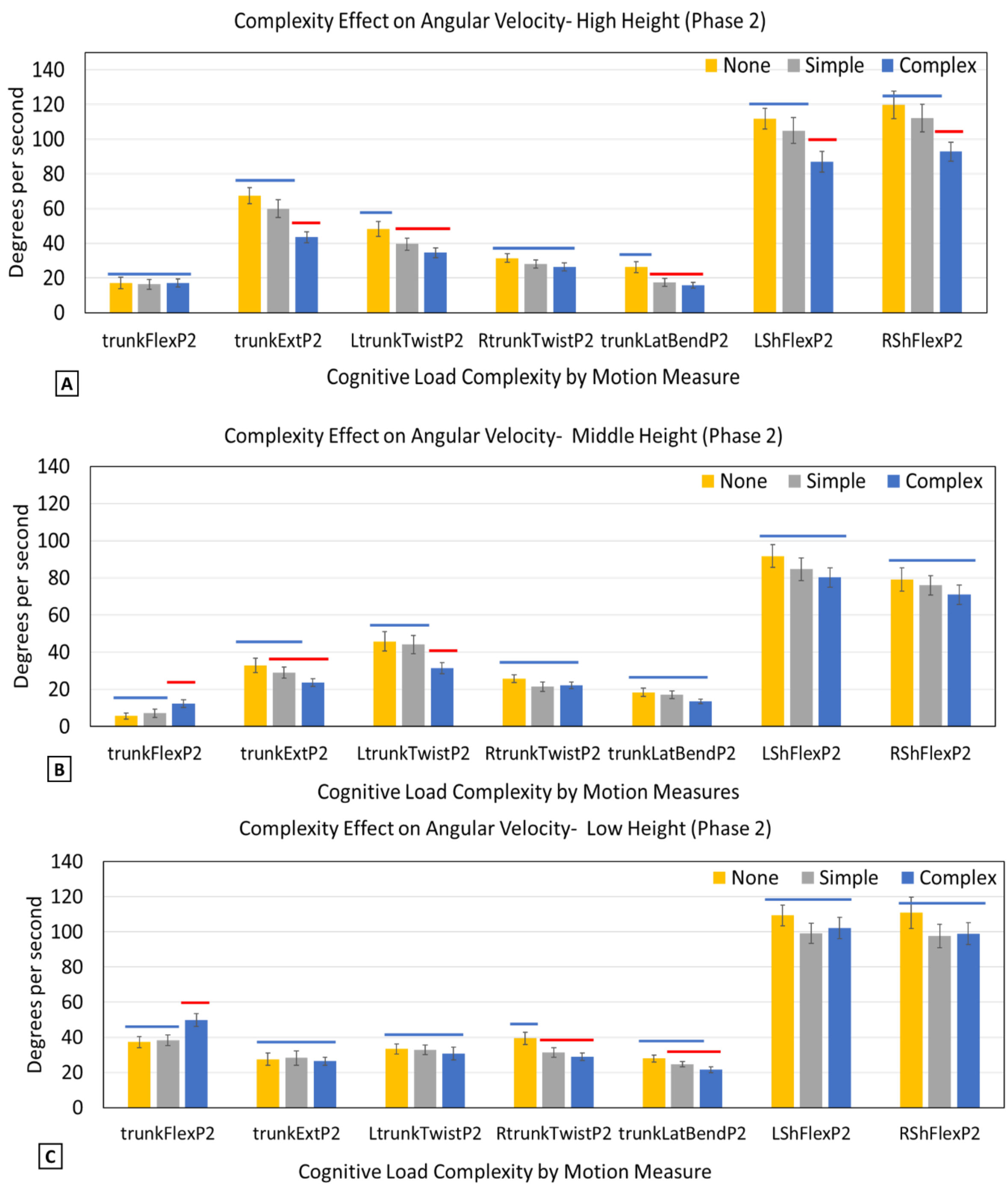


Figure 4.4: Cognitive Workload Effect for Kinematic Measures in Phase 2 for the Trunk and Shoulders for each Destination Height: (A) High Height, (B) Middle Height, and (C) Low Height. Horizontal bars that have different colors and positions between conditions represent statistically significant differences.

Muscle Activity

90^{th} Percentile EMG Analysis

A table listing the significant main and interaction effects for 90^{th} percentile normalized muscle activity values is provided below in **Table 4.4**. The analysis of 90^{th} percentile (representing peak) values focused solely on the second part of each trial, the load placement component, as described in previous sections. **Table A.2** in **Appendix A** defines the abbreviations used in the analysis of muscle activities. Nearly all of the muscles examined (aside from the right rectus abdominus) showed significant cognitive workload main effects. For the precision main effects, the left and right anterior deltoids and the left and right erector spinae muscles showed significant main effects. The right latissimus dorsi also had a marginally significant complexity effect (p= 0.051). A few significant interaction effects were observed for cognitive workload*height, precision* height, and cognitive workload* precision and those results will be examined later in this chapter.

Table 4.4: P-values for 90^{th} Percentile EMG Data Main and Interaction Effects

Significance Table- 90th Percentile							
Muscle	**Complexity**	**Precision**	**Height**	**C*H**	**P*H**	**C*P**	**C*P*H**
ADL	<0.001	0.0289	<0.001	NS	NS	NS	NS
ADR	<0.001	0.0035	<0.001	NS	NS	NS	NS
ERSL	0.0036	0.0019	<0.001	0.052	NS	NS	NS
ERSR	0.003	0.0087	<0.001	NS	NS	0.0314	NS
EXOL	<0.001	NS	<0.001	0.0062	NS	NS	NS
EXOR	<0.001	NS	0.0095	0.0179	0.0058	NS	NS
LATL	<0.001	NS	NS	0.045	0.065	NS	NS
LATR	0.001	0.0512	0.0293	NS	NS	NS	NS
ABDL	0.0244	NS	<0.001	NS	NS	NS	NS
ABDR	NS	NS	<0.001	NS	NS	NS	NS

Figure 4.5 shows the effect of cognitive workload on muscle activity across the 11 subjects. For nearly all of the muscles, the no added cognitive workload condition resulted in the highest 90th percentile normalized muscle activity levels while the Complex conditions had the lowest values. The anterior deltoids (ADL and ADR) had the most pronounced effects based on their magnitudes. The left and right anterior deltoids and left latissimus dorsi all showed significant differences between each level of cognitive workload. The left and right erector spinae, the right latissimus dorsi, and the left and right external oblique muscles had no significant difference between the None and Simple cognitive workload conditions, but both showed significantly higher values than the Complex condition. However, as described in **Section 4.5** below on the complexity by precision interaction effect, the main complexity effect for the right erector spinae was observed as a function of precision with the low precision accounting for the most differences. Additionally, the complexity main effects for the left erector spinae, the left external oblique, the left latissimus dorsi, and the right external oblique were also primarily affected by height, as described in **Section 4.6.** In the left rectus abdominus, the None had significantly lower %MVC values than the Complex conditions. The differences between the None and Simple conditions and the Simple and Complex conditions were not statistically significant. **Table B.2** in **Appendix B** provides the mean and changes in 90^{th} percentile values across the complexity conditions.

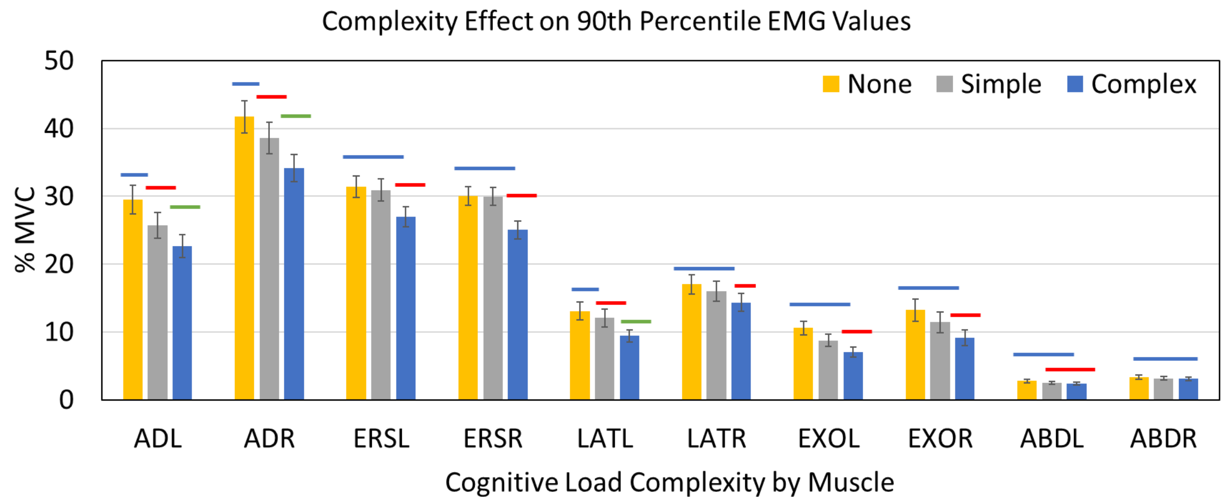


Figure 4.5: Cognitive workload effect on 90th Percentile Normalized EMG Values. Horizontal bars that have different colors and positions between conditions represent statistically significant differences.

Integrated EMG Analysis

For the analysis of the integrated EMG data, muscle activity was normalized to each subject's % maximum voluntary contraction and then summed across all frames in the trial, after trimming as described in **Section 3.7**. Each frame was 1/1000 of a second (1 Hz). **Table A.2** in **Appendix A** defined the abbreviations used in the analysis of muscle activities. **Table 4.5** below shows the outcomes from the statistical analysis of the integrated muscle activity values. Only the left and right erector spinae and rectus abdominus muscles have significant cognitive workload main effects. **Figure 4.6** shows that, for these muscles, the complex conditions had higher integrated values compared to the other two conditions. This trend, although not significant, can be seen in other muscles like the anterior deltoids and the right external oblique. For precision effects, the right erector spinae, the right external oblique, the left and right latissimus dorsi, and the left rectus abdominus muscles have significant precision effects. Several muscles showed significant cognitive workload*height and precision*height effects, which are highlighted in green in the table. **Table B.3** in **Appendix B** provided the means and value changes across complexity conditions.

Table 4.5: P-values for Integrated EMG Data Main and Interaction Effects

Significance Table- Integrated Values							
Muscle	**Complexity**	**Precision**	**Height**	**C*H**	**P*H**	**C*P**	**C*P*H**
ADL	NS	NS	<0.001	NS	0.0624	NS	NS
ADR	NS	NS	<0.001	0.0207	0.0068	NS	NS
ERSL	<0.001	NS	<0.001	NS	0.0442	NS	NS
ERSR	<0.001	0.0156	0.0019	NS	0.014	NS	NS
EXOL	NS	NS	<0.001	0.0243	0.0083	NS	NS
EXOR	NS	0.005	<0.001	0.009	NS	NS	NS
LATL	NS	0.0014	<0.001	NS	NS	NS	NS
LATR	NS	0.0435	<0.001	0.007	NS	NS	NS
ABDL	0.0095	0.015	<0.001	NS	0.0172	NS	NS
ABDR	0.009	0.077	<0.001	NS	0.0033	NS	NS

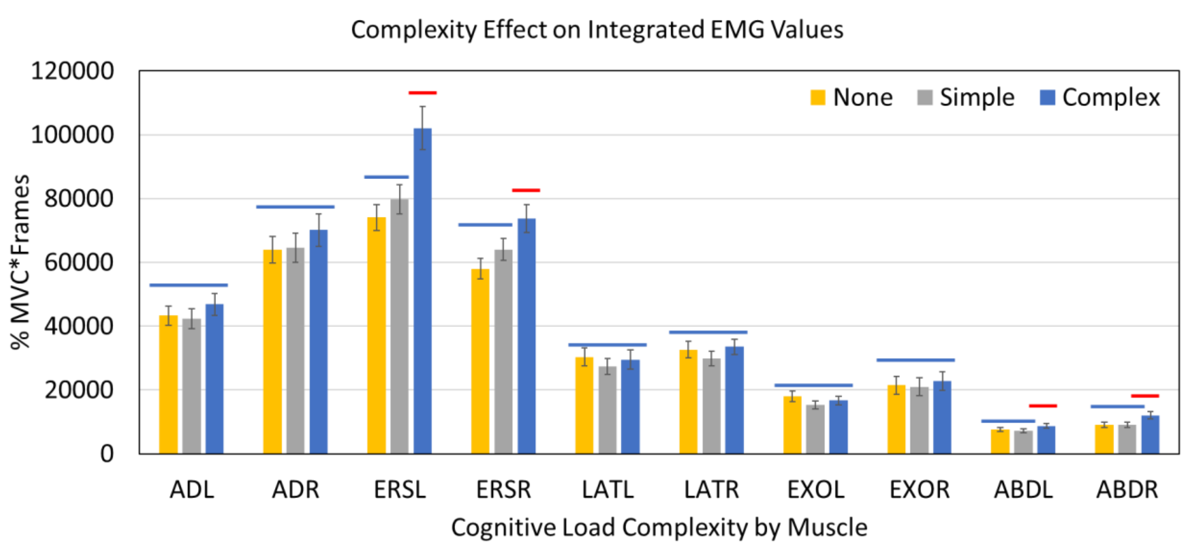


Figure 4.6: Cognitive Workload Effects on Integrated Normalized EMG Values (%MVC*Frames [1 Frame = 1/1000 Second]). Horizontal bars that have different colors and positions between conditions represent statistically significant differences.

4.4 Precision Main Effect

The following subsections describe the effects of precision on kinematics and muscle activity. The first subsection describes the effects of precision on the kinematic measures. The subsections afterward examine the effects on muscle activity, first for the 90th percentile values, then for the integrated values.

Kinematics

Phase 1

There were no main effects of task precision on the kinematics during phase 1.

Phase 2

The effect of task precision on the kinematic measures was analyzed separately by destination height. **Figure 4.7** shows the precision effects for each destination height. In all cases where significant differences occurred, the velocities in the Low Precision condition were higher than the velocities in the High Precision condition. At the high destination height, the Left Trunk Twist velocity was significantly higher in the Low Precision compared to the High Precision condition. A similar, although non-significant trend, was seen for Right Shoulder Flexion. For the Middle and Low destination heights, the same trend was observed where the Low Precision resulted in significantly larger angular velocities compared to the High Precision. For the Middle height, this trend occurred in the Left Trunk Twist, Left Shoulder Flexion, and Right Shoulder Flexion velocities. For the Low destination height, the same trend occurred for the Trunk Lateral Bend, Left Shoulder Flexion, and Right Shoulder Flexion velocities. **Table B.4** in **Appendix B** details the mean and changes in angular velocity for each of these significant kinematic measures.

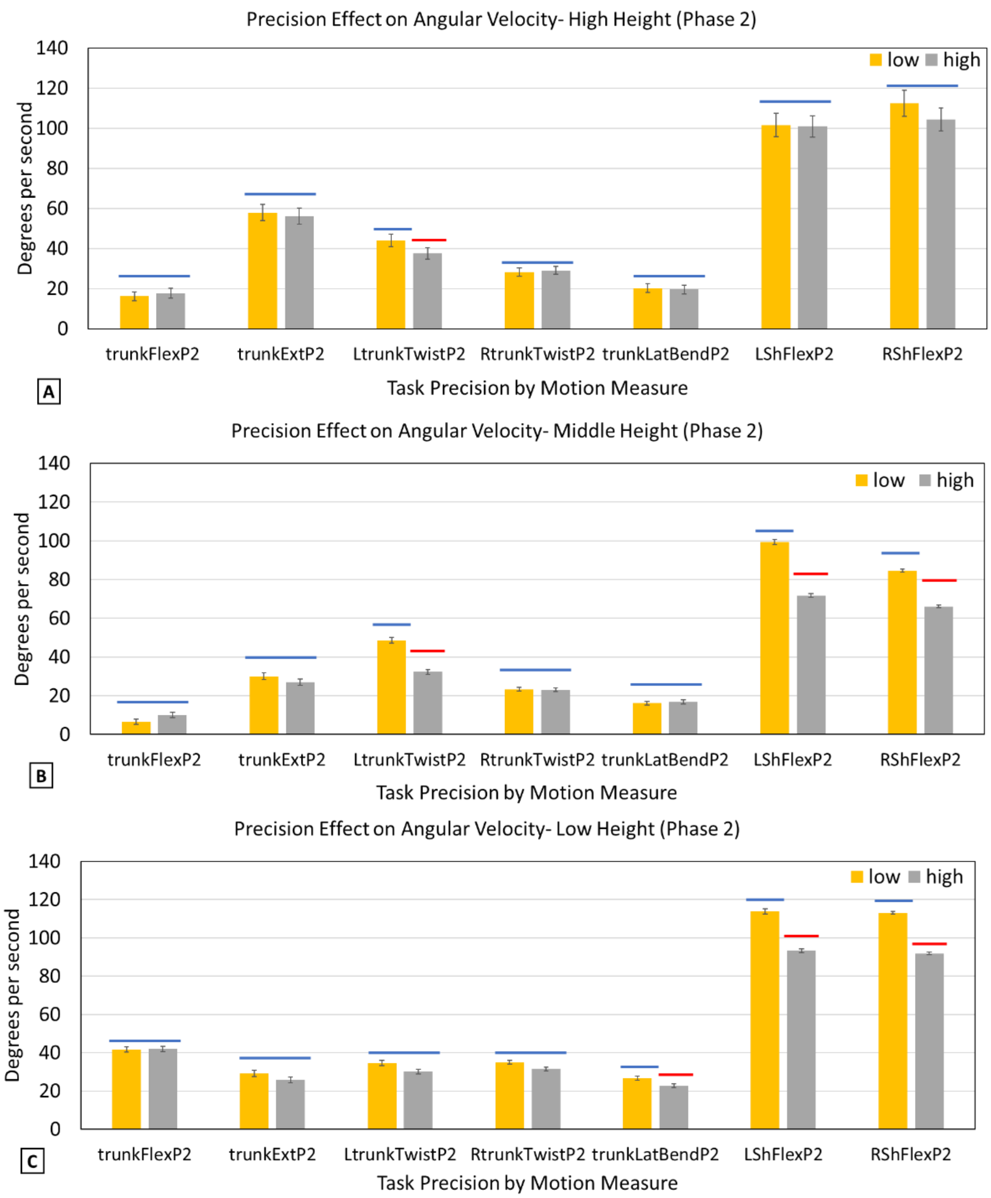


Figure 4.7: Precision Effects on Kinematic Measures in Phase 2 for the Trunk and Shoulders for each Destination Height: (A) High Height, (B) Middle Height, and (C) Low Height. Horizontal bars that have different colors and positions between conditions represent statistically significant differences.

Muscle Activity

90th Percentile EMG Analysis

Figure 4.8 shows the normalized 90th percentile muscle activity as a function of task precision level. Both anterior deltoids and erector spinae muscles were significantly different between precision levels. The right latissimus dorsi also had a marginally significant difference ($p=0.051$). Across the muscle groups that had significant precision effects, the higher 90th percentile values were seen in the Low Precision conditions. **Table B.5** in **Appendix B** provides the means and changes in %MVC for the 90th percentile values in each muscle that was significantly affected by task precision.

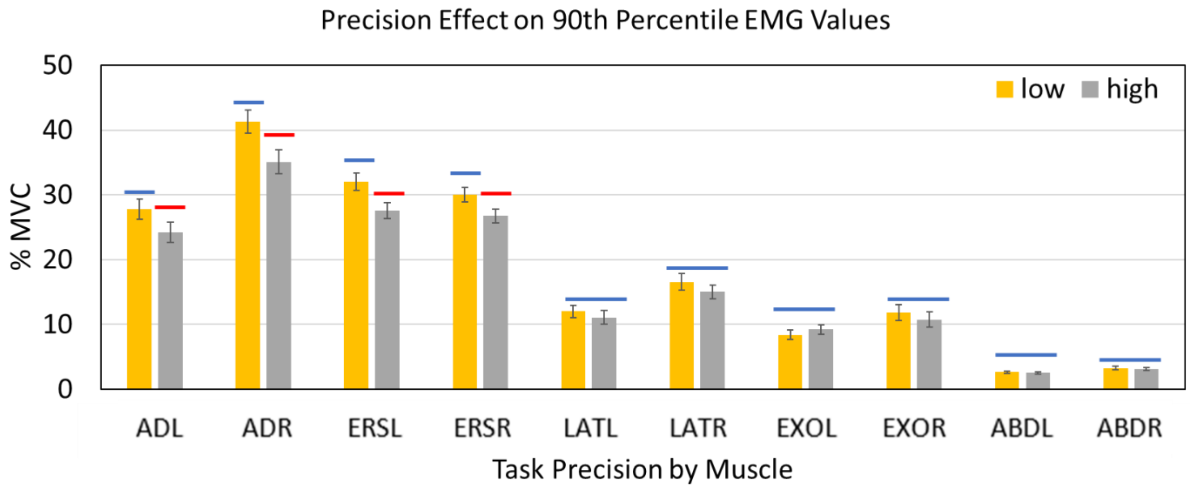


Figure 4.8: Precision Effect on 90th Percentile Normalized EMG Values. Horizontal bars that have different colors and positions between conditions represent statistically significant differences.

Integrated EMG Analysis

The task precision was analyzed for its effect on the cumulative muscle activity for trunk and shoulder muscles. **Figure 4.9** shows that a significant precision effect was found for the right erector spinae, left and right latissimus dorsi, right external oblique, and left rectus abdominus muscles. For each of these muscles, the High Precision condition resulted in a significantly higher integrated value compared to the Low Precision condition. This trend can also be seen in the muscles that did not have statistically significant precision effects. For the right anterior deltoid, right erector spinae, and the left rectus abdominus, the main precision effect was observed in only the low height as described in **Section 4.7**. In **Appendix B**, **Table B.6** provides the mean and changes in significant integrated normalized EMG values between the Low and High Precision conditions.

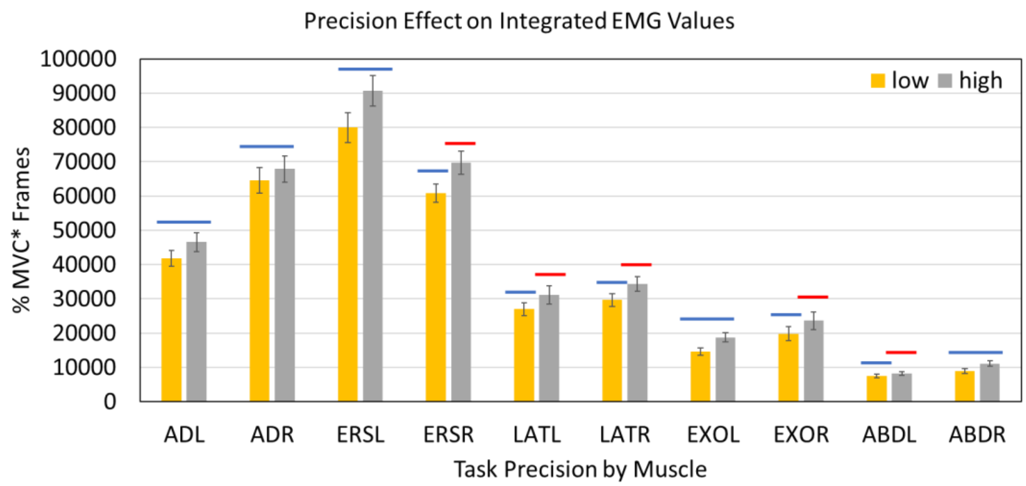


Figure 4.9: Precision Effect on Integrated Normalized EMG Values (%MVC*Frames [1 Frame = 1/1000 Second]). Bars that have different colors and positions between conditions represent statistically significant differences.

4.5 Cognitive Workload*Precision Interaction Effect

The following subsections described the significant interaction effects of cognitive workload*precision on kinematics and muscle activity. A Bonferroni adjustment was made to account for the 2 sub-analyses by dividing the alpha value of 0.05 by 2.

Kinematics

Phase 1

Following up on results from the statistical analysis that were presented in Table 4.2, an analysis of the interaction effect of cognitive load level and task precision on angular velocity was completed for the Trunk Flexion, Left Shoulder Flexion, Left Trunk Twist, and Right Shoulder Flexion velocities observed during phase 1 of the kinematics analysis. **Figure 4.10** plotted the cognitive workload*precision interaction effect for these measures. For the Trunk Flexion velocities, a significantly lower velocity was observed for the Complex cognitive workload condition for the Low Precision conditions compared to both the None and Simple conditions. In the High Precision condition, a significantly larger velocity in the None condition compared to the Simple and Complex conditions was observed. This trend was also observed for the Left Trunk Twist and Left Shoulder Flexion measures in the High Precision conditions. In the Low Precision condition for Left Trunk Twist, only the None condition and Complex conditions were significantly different, with the Complex condition having the lower velocity. For the Left Shoulder Flexion, each level of cognitive load complexity significantly differed in the Low Precision with a trend of decreasing velocities as cognitive load complexity increased. This same trend was observed for both precision levels in Right Shoulder Flexion measures.

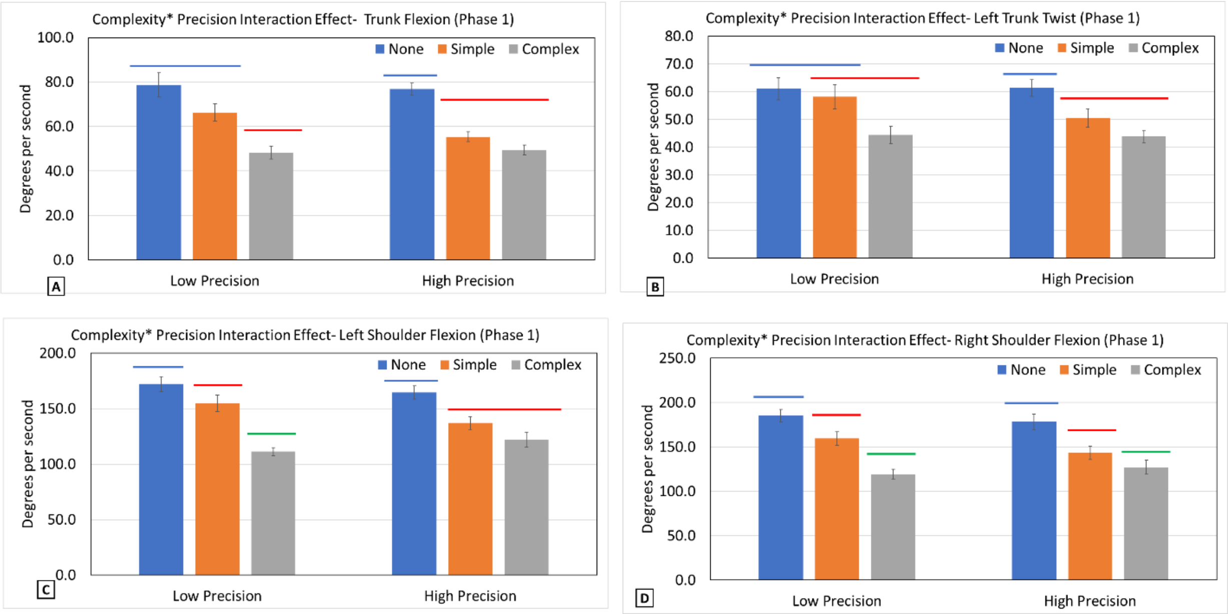


Figure 4.10: Cognitive workload*Precision Interaction Effect for Kinematic Measures (Phase 1) for (A) Trunk Flexion, (B) Left Trunk Twist, (C) Left Shoulder Flexion, and (D) Right Shoulder Flexion. Horizontal bars that have different colors and positions between conditions represent statistically significant differences.

Phase 2

Following up on the results of the statistical analysis presented in Table 4.3, an analysis was conducted of the interaction effect of cognitive load and task precision on Right Shoulder Flexion velocity when placing the box at the low destination height. **Figure 4.11** shows the results following a Bonferroni adjustment to account for the 2 subdivisions of analysis. The analysis identified lower angular velocities for Complex conditions compared to the None and Simple condition for both Low and High precision conditions.

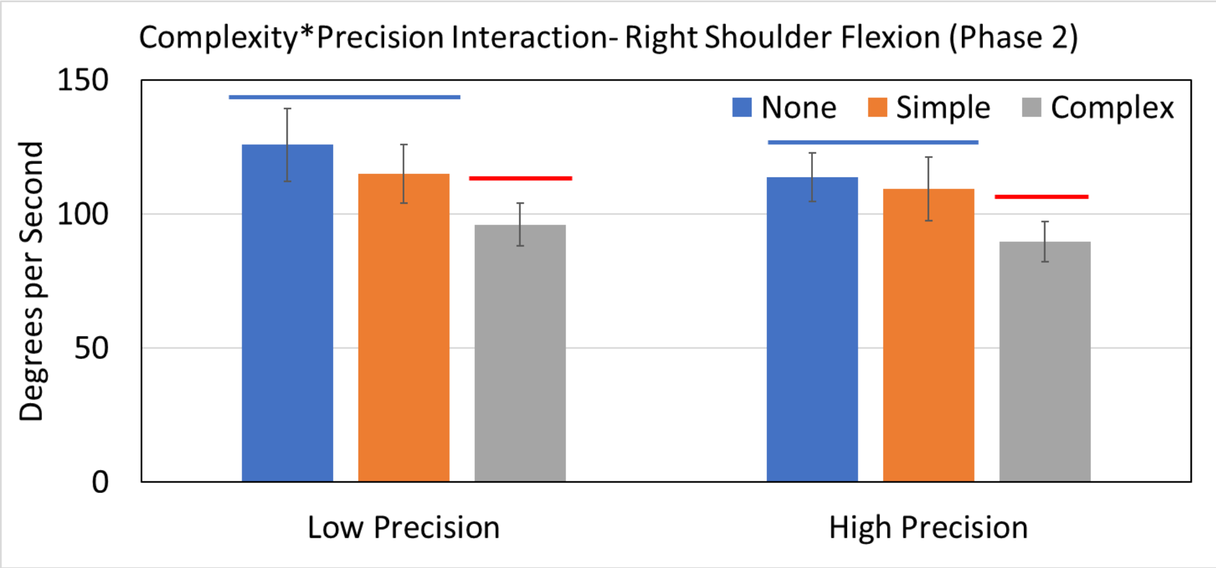


Figure 4.11: Complexity*Precision Interaction Effect for Right Shoulder Flexion (Phase 2) for Low Destination Height. Horizontal bars that have different colors and positions between conditions represent statistically significant differences.

Muscle Activity

90th Percentile EMG Analysis

Figure 4.12 shows the interaction effect of task precision on cognitive load level for the normalized 90th percentile muscle activity values in the right erector spinae. Post hoc analysis, after applying a Bonferroni correction (0.05/2), identified a significantly lower 90th percentile value for the Complex cognitive workload condition compared to the Simple condition in the Low Precision and a significantly lower 90th percentile value for the Complex condition compared to the None condition for the High Precision.

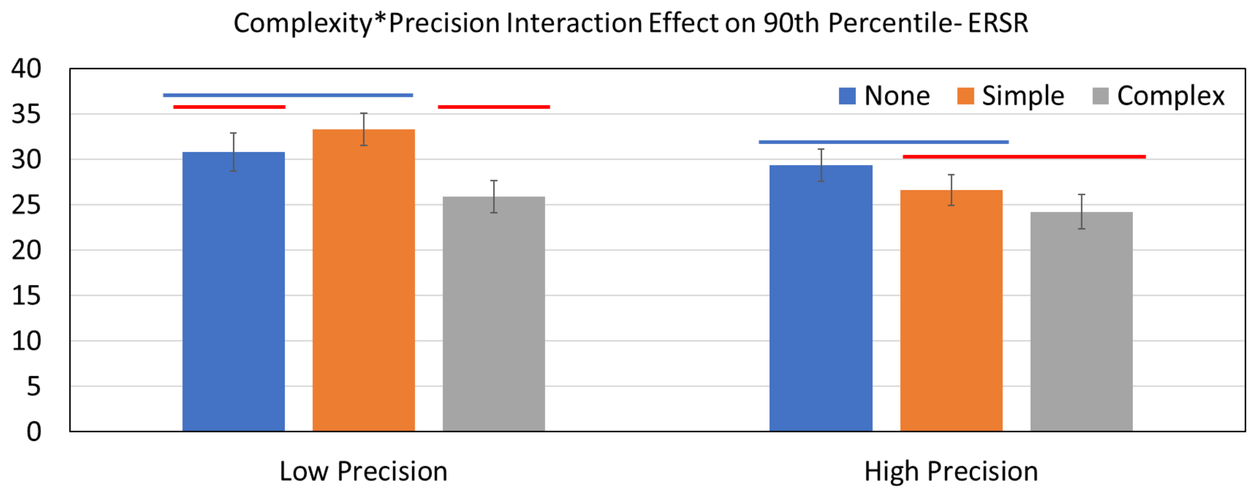


Figure 4.12: Cognitive Workload*Precision Interaction Effect for Right Erector Spinae (90^{th} Percentile Normalized EMG Value). Horizontal bars that have different colors and positions between conditions represent statistically significant differences.

Integrated EMG Analysis

None of the integrated EMG analyses showed significant cognitive workload*precision interaction effects.

4.6 Cognitive Workload*Height Interaction Effect

The following subsections described the significant interaction effects of cognitive workload*height on kinematics and muscle activity measures. The following subsection examined the effects on kinematics for the first phase of the lifting task. The second phase of the task was excluded due to the cognitive workload effect already having been examined by destination height for this phase in **Section 4.2**. The subsections afterwards examined the effect on muscle activity, first for the 90^{th} percentile values then for the integrated EMG values. Note that a number of measures did not have significant interaction effects between cognitive workload and height. Only interactions that had significance values <.05 were investigated and some of these were not significant in post-hoc analysis.

Kinematics

Phase 1

While significant interactions were found for the Trunk Extension, Left Shoulder Extension, Right Shoulder Extension, and Trunk Lateral Bend velocities (**Table 4.2**), the Bonferroni adjustment did not find significant effects for the Right Shoulder Flexion velocity. **Figure 4.13A** illustrates that trunk extension velocity was only affected by differences in cognitive workload at the low destination height. The more challenging workload condition resulted in a significantly larger angular velocity compared to both the None and Simple conditions. For Trunk Lateral Bend (**Figure 4.13B**) there were differences at the High destination height, wherein the Complex conditions had a significantly lower angular velocity for this measure compared to the None and Simple Conditions. For the Left Shoulder Extension (**Figure 4.13C**), at both the Low and High destination heights the Complex conditions had significantly lower angular velocity than the None conditions, however the None and Simple conditions and the Simple and Complex conditions did not differ significantly. Additionally, the Middle height observed a significantly lower angular velocity in the Complex condition compared to the None and Simple conditions.

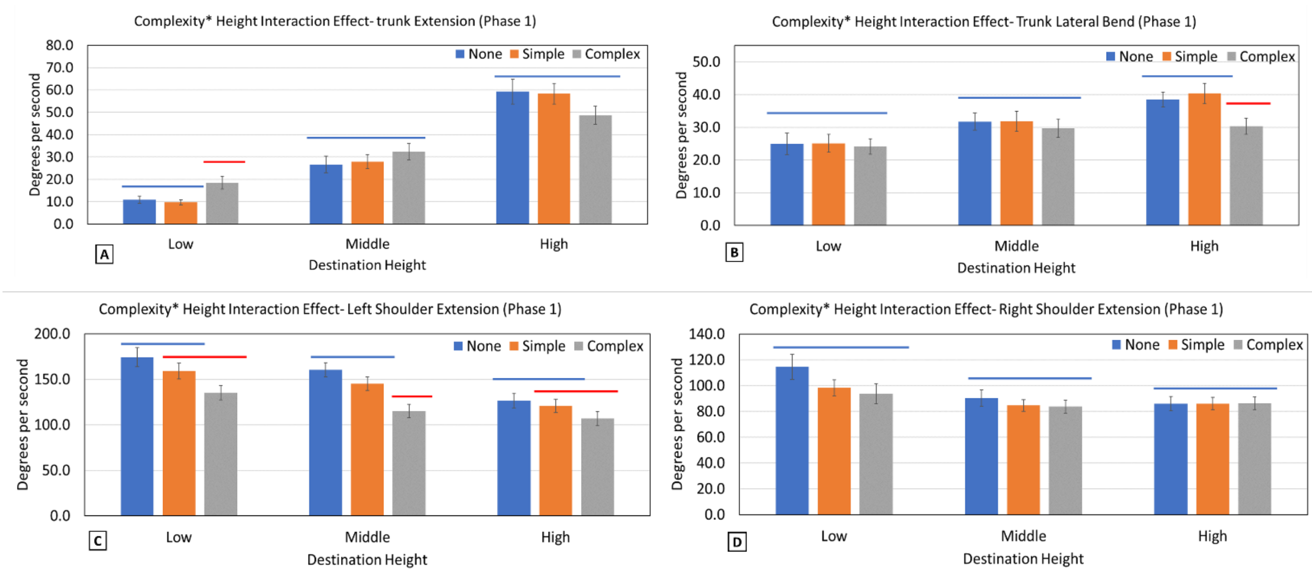


Figure 4.13: Cognitive Workload*Height Interaction Effect for Kinematic Measures (Phase 1) for (A) Trunk Extension, (B) Trunk Lateral Bend, (C) Left Shoulder Extension, and (D) Right Shoulder Extension. Horizontal bars that have different colors and positions between conditions represent statistically significant differences.

Muscle Activity

90th Percentile EMG Analysis

After applying the Bonferroni correction (0.05/3), a significant post hoc effect was found for the left erector spinae in the High height condition wherein the muscle's activation during the higher cognitive workload condition was significantly lower than in the None and Simple conditions (**Figure 4.14A**). A similar finding occurred for the left external oblique, though for the low destination height (**Figure 4.14B**).

For the left latissimus dorsi, the effects of cognitive workload were similar for the middle and high shelf heights. At both heights, the none and higher cognitive workload levels were significantly different. There was no effect of cognitive workload at the low shelf level for the left latissimus dorsi (**Figure 4.14C**). For the right external oblique, the effects of cognitive workload were only seen at the middle shelf height. At that height, the none and higher cognitive workload levels were significantly different. There was no effect of cognitive workload at the low or high shelf levels for the right external oblique (**Figure 4.14D**).

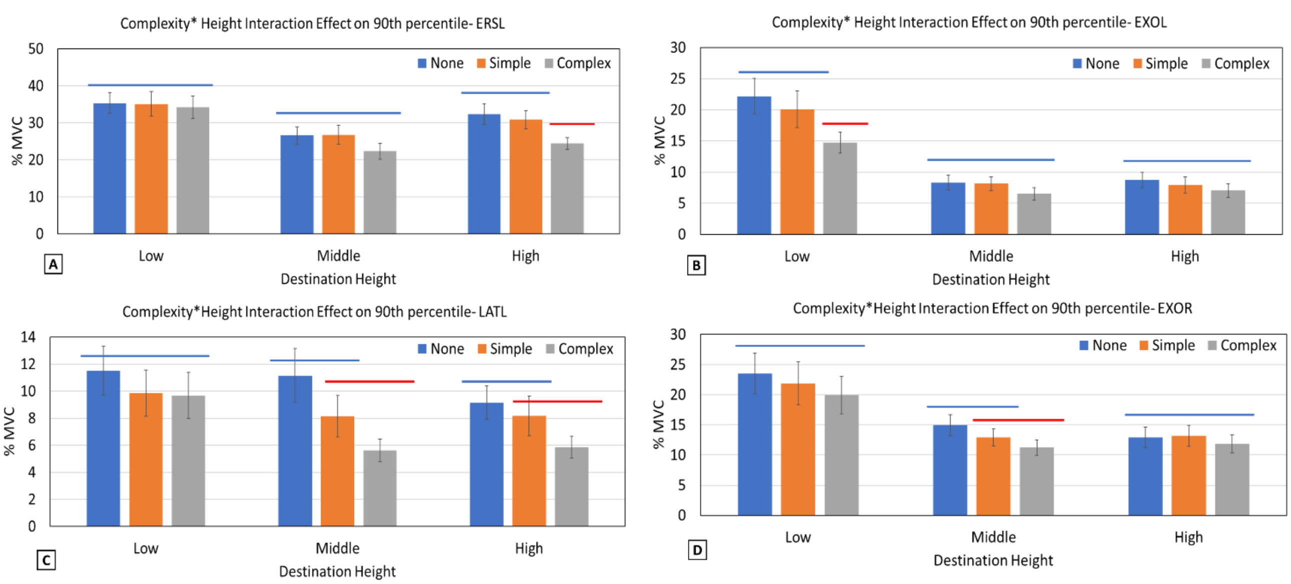


Figure 4.14: Cognitive Workload*Height Interaction Effect for 90th Percentile Normalized EMG Values for (A) Left Erector Spinae (B) Left External Oblique, (C) Left Latissimus Dorsi, and (D) Right External Oblique. Horizontal bars that have different colors and positions between conditions represent statistically significant differences.

Integrated EMG Analysis

While a significant interaction effect of cognitive load and destination height was detected for the normalized cumulative (integrated) muscle activity in the right anterior deltoid, left external oblique, right latissimus dorsi, and right external oblique muscle (Table 4.5), none of the measures were found to have significant interaction effects in post hoc testing after the Bonferroni adjustment (0.05/3). **Figure C.1** in **Appendix C** provides plots for these measures.

4.7 Precision*Height Interaction Effect

The following subsections describe significant interaction effects of precision*height on kinematics for the first phase. The second phase was excluded due to the precision effect already having been examined by destination height for this phase in **Section 4.3**.

Kinematics

Phase 1

After applying a Bonferroni adjustment (0.05/3), neither the Left nor Right Shoulder Extension velocities, which had shown significant overall interaction effects, had significant differences in these velocities when compared across height levels (**Figure C.2** in **Appendix C**).

Muscle Activity

90th Percentile EMG Analysis

The significant task precision by destination height interaction effect was further analyzed for the 90th percentile normalized left latissimus dorsi and the right external oblique EMG values after applying a post-hoc Bonferroni correction (0.05/3). With this correction neither of the interactions showed significant changes due to the precision requirements at the different destination heights (**Figure C.3** in **Appendix C**).

Integrated EMG Analysis

While the initial ANOVA showed significant task precision by destination height interaction effects for the cumulative muscle activities in the left and right anterior deltoids, erector spinae, rectus abdominus and left external oblique muscles, the post-hoc analysis with a Bonferroni adjustment (.05/3) showed significant interactions only for the right anterior deltoid, right erector spinae, and left rectus abdominus muscles. **Figure 4.15** shows that for all three muscles, a significant effect was found at the Low height only, with the High Precision condition resulting in a significantly higher integrated value compared to the Low Precision condition. There were no differences due to task precision at the middle or high heights for those muscles.

The left anterior deltoid, left erector spinae, left external oblique, and right rectus abdominus were not found to have significant interaction effects in post-hoc testing. Plots of the interaction effect for these muscles are provided in **Figure C.4** in **Appendix C**.

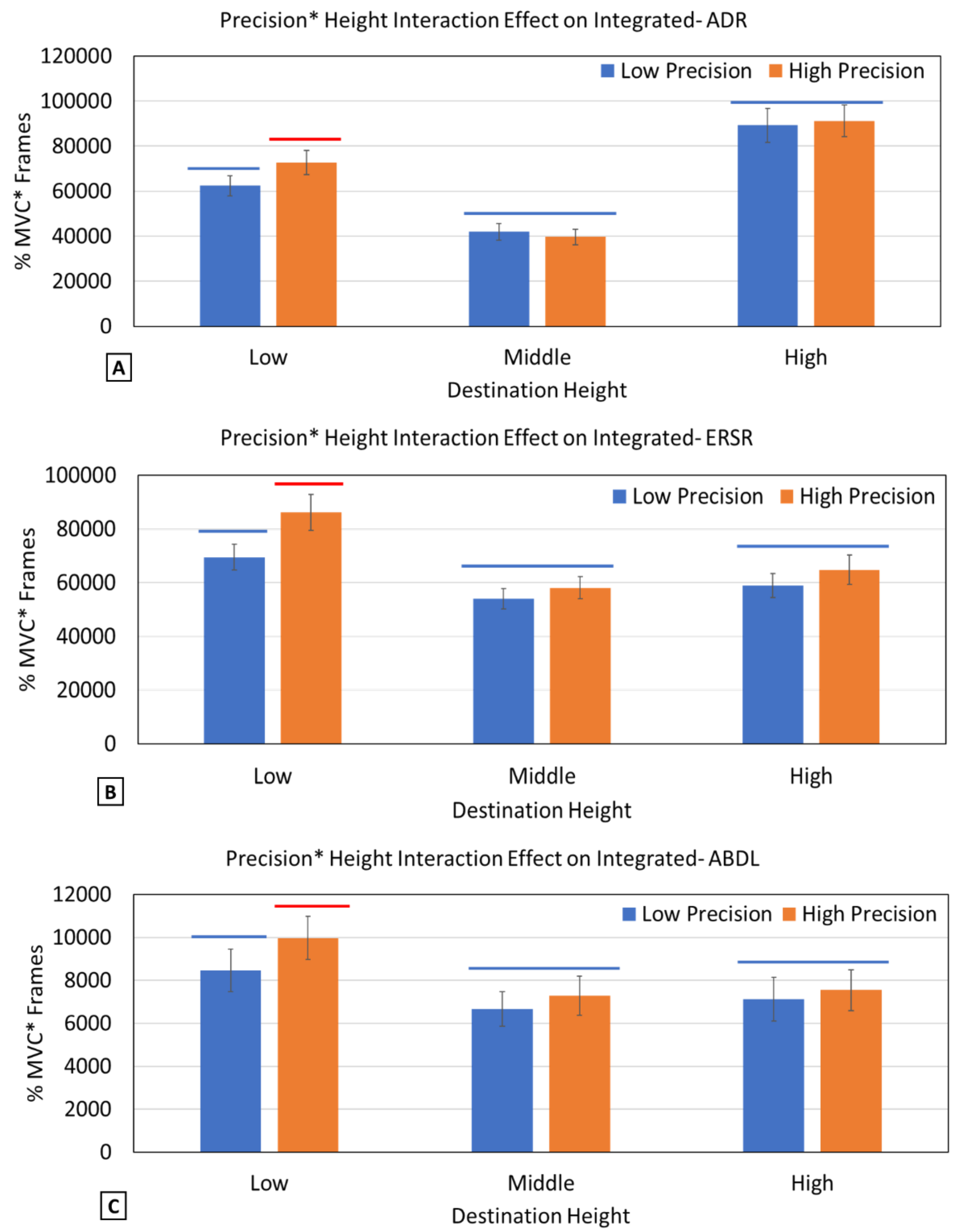


Figure 4.15: Precision*Height Interaction Effect for Integrated Normalized EMG Values for (A) Right Anterior Deltoid, (B) Right Erector Spinae, and (C) Left Rectus Abdominus. Note that integrated values were calculated by summing the normalized EMG value for each frame (where 1 Frame = 1/1000 Second). Horizontal bars that have different colors and positions between conditions represent statistically significant differences.

4.8 Results Summary

Phase 1 Kinematics

For Phase 1 angular velocity measures, significant cognitive load complexity effects were observed for Trunk Flexion, Left Trunk Twist, Left Shoulder Flexion, Left Shoulder Extension, and Right Shoulder Flexion. Of these, Trunk Flexion, Left Trunk Twist, Left Shoulder Flexion, and Right Shoulder Flexion's significance depended on the precision condition. Additionally, the significance of the complexity effect for Left Shoulder Extension, Trunk Extension, and Trunk Lateral Bend relied on the destination height. For all of these segments (excluding Trunk Extension which observed a significant increase), angular velocity significantly decreased with increased complexity. No significant precision effect was observed for this phase.

Phase 2 Kinematics

In Phase 2 of the kinematics analysis, significant complexity effects were observed for Trunk Extension in the High and Middle heights, Left Trunk Twist in the High and Middle heights, Trunk Lateral Bend in the High and Low heights, Left Shoulder Flexion in the High Height, Right Shoulder Flexion in the High height, Trunk Flexion in the Middle and Low heights, and Right Trunk Twist in the Low height. Each of these measures observed a significant decrease in angular velocity with increased cognitive load complexity aside from the Trunk Flexion measures in the Middle and Low heights which observed a significant increase with increased complexity. Significance in the Right Shoulder Flexion for the Low height was dependent on precision level. Significant decreases in angular velocity due to precision were also observed for the Left Trunk Twist in the High and Middle heights, Trunk Lateral Bend in the Low height, and Left and Right Shoulder Flexions for both the Middle and Low heights.

90th Percentile EMG

For normalized, near-peak (90th Percentile) values, a significant cognitive load complexity effect was observed for the left and right anterior deltoids, left and right erector spinae, the left and right latissimus dorsi, the left and right external obliques, and the left rectus abdominus. The significance of the complexity effect for the right erector spinae was dependent on the precision level. Additionally, the significance of the left erector spinae, left latissimus dorsi, and left and right external obliques were dependent on the destination height. Each of these muscles observed a significant decrease in 90th percentile normalized activity with increased cognitive load complexity. A significant decrease in near-peak muscle activity with increased precision requirements was also observed for the left and right anterior deltoids and left and right erector spinae muscles. The effects were observed regardless of height conditions.

Integrated EMG

A significant cognitive load effect was observed for the cumulative activity of the left and right erector spinae and left and right rectus abdominus muscles. As cognitive load complexity increased, significantly larger cumulative muscle activity values were observed. The cognitive load effects observed were not significantly affected by precision or height. Additionally, significant increases in cumulative activity were observed with increased precision for the right erector spinae, left and right latissimus dorsi, right external oblique, and left rectus abdominus. Destination height significantly affected the effect of precision for the right anterior deltoid, right erector spinae, and left rectus abdominus—all of which only had significant effects in the Low destination height.

Chapter 5. Discussion

5.1 Task completion time, EMG, and Kinematics

The findings in this study supported some but not all of the hypotheses. The first hypothesis, that an increase in cognitive load and task precision would lead to increased task completion time, was supported by the analysis. As cognitive load increased, completion time also significantly increased for each level. Similarly, across the two levels of precision, completion time also increased with increased precision. The observation that completion time and question difficulty ratings significantly increased as cognitive workload level increased validated that the design of the questions were properly formulated to identify a dose-response relationship for difficulty level. Since the Simple and Complex conditions had significant differences in their subjective ratings, they represented two distinct levels of cognitive load, as intended. In addition, the significant differences in completion time across the levels of cognitive workload further emphasized a difference in difficulty across levels.

The second hypothesis, which theorized an increase in muscle activity with increased cognitive workload, was partially supported. In the 90th percentile normalized EMG analysis, the higher cognitive workload conditions resulted in significantly lower near-peak (90th percentile) EMG values, which contradicted the hypothesis. These results were seen for all the muscles examined, except for the right rectus abdominus. In the analysis of the cumulative (integrated) EMG activity over time, a significantly larger cumulative muscle activity was observed in the higher cognitive workload conditions for the erector spinae and rectus abdominus muscles.

Studies examining the effect of cognitive loads on shoulder muscle activity in light manual tasks have observed similar decreases in peak muscle activity. MacDonell & Keir (2005) examined the effect that a simultaneous cognitive task and specified grip force had on shoulder maximum exertions. They identified that the cognitive task significantly decreased the moment and muscle activity during maximum strength tests. Au & Keir (2007) conducted a similar study where participants performed hand and shoulder exertions with combinations of grip precision force, mental load, and shoulder load conditions. They identified that the mental task paired with the 40% shoulder moment conditions significantly increased trapezius activity by nearly 2% MVE (maximum voluntary exertion) while the mental task condition reduced all deltoid activity by 1% MVE. Larger differences were observed in the current study. 90th percentile deltoid activity was reduced by ~7% in the Complex cognitive load condition compared to the non-loaded condition. This larger difference could likely be attributed to the increased physical demand of the task in this study. Mehta & Agnew (2013) compared the muscle activity of the shoulders when under a concurrent physical and mental arithmetic workload during intermittent shoulder exertions. The addition of mental demands to mechanical workload decreased activity in the affected muscles, mental task performance, and subjective workload measures. In particular, they identified a significant decrease in EMG activity due to mental task during exertions with high physical demand.

The effects of Task Precision also differed between the two characterizations of muscle activity. For the anterior deltoid and erector spinae muscles where differences were detected, significantly larger normalized 90th percentile EMG values were observed for the Low Precision conditions, while for the right anterior deltoid, right erector spinae, left and right latissimus dorsi, right external oblique, and left rectus abdominus muscles where significant differences were detected in the cumulative activity, values were larger for the High Precision conditions. However, in the right erector spinae and left rectus abdominus, the cumulative effect was only significant for the low destination height. Additionally, the right erector spinae was the only muscle that showed a significant effect for both the 90th percentile and cumulative activity measures. Joseph et al.'s (2014) study on the influence of precision and cognitive load on upper extremity joint reaction forces, moments, and muscle forces observed results similar to those in the current study. Both their combination task (high precision and high cognitive load) and their high precision task alone led to 18% smaller maximal forces and moments while producing up to 43% larger cumulative forces and moments than either their control and cognitive distraction conditions. Similar conclusions were made on the cause of this behavior. They identified that the higher precision led to longer lift times and therefore larger cumulative forces and moments, with lower peak forces and moments due to lower accelerations. Milerad & Ericson, (1994) study on the effect of high precision and force demands on muscle activity in the upper extremity observed the opposite trend. Their study simulating dentistry work identified a significant increase of muscular load from precision on the extensor carpi radialis, infraspinatus, and trapezius muscles. The difference in these findings suggest a discrepancy between precision effects due to fine hand work versus more ballistic movements associated with rapid lifting tasks.

The third hypothesis that theorized an decrease in torso and arm movement velocities due to increases in task precision and cognitive load was supported. The findings identified significant decreases in several phase 1 and phase 2 angular velocities with increased cognitive workload. The exception to this was the Trunk Flexion velocities in phase 2 for the middle and low heights, which observed a significant increase in velocity for the higher cognitive workload conditions. This may have occurred as a result of how tasks were prioritized and completed. Participants could have prioritized the cognitive task and upon its completion, shifted their attention to the remaining motor task—placing the box at the appropriate rack height. To compensate for time lost from the cognitive task, participants could have moved rapidly during the placement task, flexing their torso more swiftly to bring their body closer to the shelf. Other studies identified similar effects on movement from dual-tasking. Villafaina et al. (2019) observed that a concurrent dual-task during an arm curl test resulted in a significant decrease in the range of movement when compared to control condition. Similarly, in a review across dual-task studies concerning gait measures, a trend of decreased speed, cadence, and stride length and increased stride time and stride time variability was observed (Al-Yahya et al., 2011). Numerous studies in the review observed slowing of gait speed as a result of a cognitive task.

The last hypothesis theorizing that the effects of cognitive load and precision would be larger at non-optimal shelf heights was partially supported. For the phase 2 kinematic measures, the Low and High heights had stronger significance levels across complexity conditions compared to the Middle height. The significance of effects for some measures also depended on the height condition as well. For example, the precision*height interaction effects for integrated EMG measures were only significant for the Low height conditions in the right anterior deltoid, right erector spinae, and left rectus abdominus muscles.

The findings from this research identify a trend of slower movement across higher cognitive workload and higher precision conditions. In the kinematics analysis, a trend was observed where the no cognitive load conditions and the Low Precision conditions separately had significantly higher values of angular velocity than the High cognitive load and High Precision conditions. This identified a slowing of movement speed when participants were under the dual-task condition and was especially apparent in the high cognitive workload condition. This reduction in movement speed may represent the shifting prioritization of resources from the movement task to the cognitive load task for the higher cognitive load conditions. Similarly, the 90^{th} percentile normalized EMG values were larger for nearly all muscles in the None condition than the higher cognitive load condition. This aligns with the kinematic results which observed faster trunk flexion and rotation. As the participant increases their movement velocity, as was the case for the None condition, the activity in muscles increases as more muscle effort is required to make these faster movements. For the higher cognitive load condition, the angular velocities were lower so the 90^{th} percentile EMG values were also lower for those conditions, while an increase in cumulative muscle activity was observed. As a result of the slower movement and the task taking longer due to the cognitive load, the duration of the participants under the mechanically loaded condition was lengthened. This results in a larger cumulative muscle load as was observed in the erector spinae and rectus abdominus muscles in this study. This observation was similar to the one made by Joseph et al (2014), however the significant effect here was observed for both the cognitive and precision conditions compared to only the precision condition in their study.

Cognitive load task component completed concurrently with a physical task has also been shown to affect other biomechanical metrics, including estimates of joint compression forces. Katsuhira et al. (2013) observed that mental processing using arithmetic tasks significantly increased peak low back compression force and low back extension moment. The authors also examined the pelvic tilt and trunk bending angles and observed significant main effects of mental processing for the squatted posture but not the stooped posture. Davis et al. (2002) examined the effect of serial and simultaneous dual-tasking and job pacing on the biomechanical loading of the spine. They observed large significant increases in 3D spine loading from the complex mental task performed simultaneously with a material handling task. The combination of fast pacing and complex simultaneous mental processing also resulted in up to 50% greater spine loads than that of pacing alone. A 2 to7% increase in muscle activity of 10 trunk muscles was also observed under the complex simultaneous mental processing condition. In terms of kinematics, this dual processing resulted in greater trunk moments and slightly larger trunk and hip motions.

The variability of findings throughout the literature is likely due to the highly variable nature of the cognitive tasks and physical tasks used in the research. Many variations of tasks have been used to create a cognitive load including arithmetic problems, counting, spelling, precise placement requirements, memory task, visual-tracking tasks, and visual-auditory interference tests. Al Yahya et al (2011) categorized and attempted to compare the effects of the cognitive task domains in their systematic review on dual-task effect on gait. Their analysis observed that cognitive tasks that involve internal interfering factors (e.g. mental tracking tasks) seem to disrupt gait performance more than those involving external interfering factors (e.g. reaction time task). The authors theorize that cognitive tasks such as mental tracking and verbal fluency tasks share complex neural networks including those of gait control. Thus, demands from these cognitive tasks may interfere with these processes and disrupt gait. Cognitive tasks with external interfering factors (e.g. reaction time tasks), on the other hand, may interfere less as they only share stimulus-driven lower-order networks with those of gait control. The cognitive task in this study utilizes internal processes that may interfere with complex neural networks, explaining the slowed movement observed.

Some models have attempted to categorize the processing and prioritization of cognitive resources when under dual-task conditions. Tombu & Jolicœur (2003) proposed a model to describe dual-task prioritization and compared it to the simpler bottleneck model used previously to describe this behavior. The bottleneck model postulates that some processing required for tasks are dependent on processors that can only act on one input at a time. Therefore, if multiple tasks require one of these processors simultaneously, only one task can get access to it while the other is suspended until the processor is free. The general bottleneck model hypothesizes that some processes, such as stimulus identification and response execution, can be done in parallel, while processors that relate to response selection and decision making must operate on stimuli serially. This belief aligns with the one mentioned by Al Yahya above. In the bottleneck model, the processes that are able to be completed simultaneously share lower-order networks while the ones that need to be completed serially likely share higher-order networks.

The central capacity sharing model proposed by Tombu and Jolicœur expand on this idea and theorize that two tasks can be completed in parallel, however response time and performance are affected by the division of limited resources from the shared available processing capacity. Due to having limited resources, both tasks share the available processing capacity and performance is determined by a person's prioritization. This model has been adapted to describe the processing behind cognitive-motor dual-tasking. Cognitive Motor Interference (CMI) describes how simultaneous performance of a cognitive task and a motor task negatively affects the performance of one or both of the tasks due to the competing demands of shared, limited resources (Abernethy, 1988). The more demanding a task, the greater the proportion of resources required. Due to this limited processing capacity, if the combined tasks exceed a person's total capacity, task performance will deteriorate. Plummer & Eskes, (2015) proposed a method of analyzing the Dual-Task Effect (DTE) by comparing the relative interference of the cognitive task on a motor task and vice-versa in a matrix style scatterplot that has positive and negative motor dual-task effect on the vertical axis, and positive and negative cognitive dual-task effect on the horizontal axis. **Figure 5.1** presents a sample of this matrix. This interference has been examined in many of the gait, upper body, and spine studies presented in the review of the literature with interference resulting in decreased performance in the motor task, cognitive task, or in both (Al-Yahya et al., 2011; Plummer et al., 2013; Norrie et al., 2021; Bank et al., 2018). Bank et al (2018) observed an increase of interference on their cognitive task (Stroop test) resulting in deteriorated performance when a higher difficulty motor task (goal-oriented arm tracking task with obstacles) was presented. Similarly, Klingberg (2000) identified that gait speed control areas seem to be interlinked with the networks of higher-level cognitive functions, in particular executive function that include the prefrontal cortex. Therefore, CMI while walking might arise when the concurrent tasks compete for these shared neural networks.

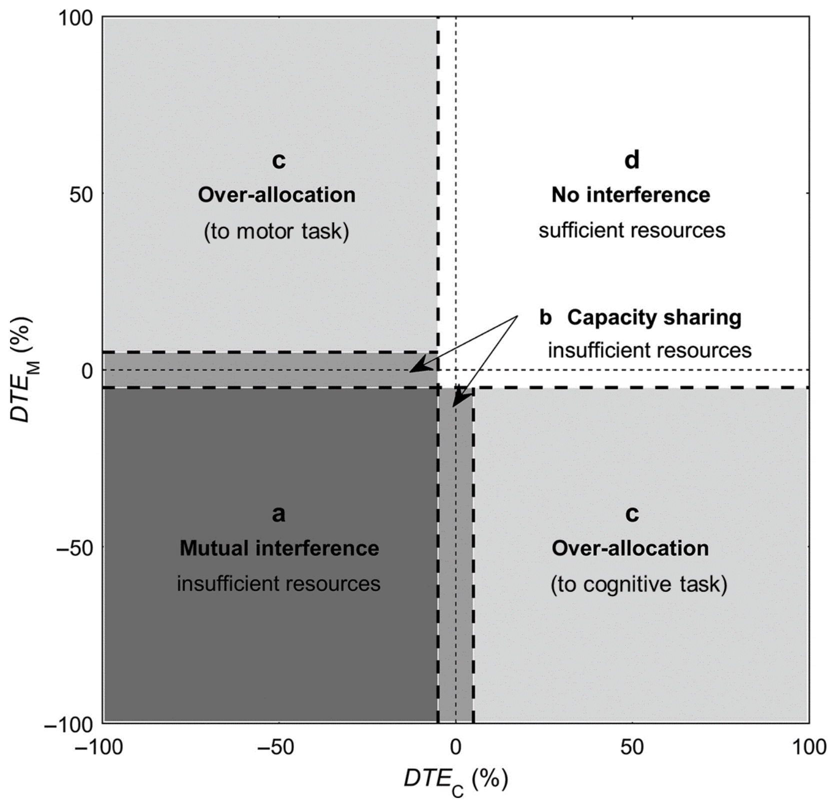


Figure 5.1 Patterns of Cognitive Motor Interference plot to analyze Dual Task Effect. (a) both tasks' performance deteriorate, (b) deteriorated performance on one of tasks but not the other (one task is prioritized when resources are insufficient); (c) improvement of one task at cost of deteriorated performance in the other task (may not necessarily be due to insufficient attentional resources); (d) no interference, indicating sufficient resources for both tasks. Figure adapted from (Bank et al., 2018).

The current study observed the effect of cognitive motor interference directly and indirectly. The findings on completion time that identified significant differences across completion time indicated an interference on the motor task performance. As cognitive workload increased, motor performance (when measured by completion time) degraded. This suggests that the Dual Task Effect for the tasks in this study, as described by Plummer & Eskes (2015), would be located between (b) and (c) in the mid-to-low right-side quadrant of **Figure 5.1.** Measuring the interference in terms of segment velocities and muscle activity was more difficult to describe in terms of positive or negative influences as they have context-driven interpretations. Peak muscle activity and angular velocities decreased with increased cognitive load, while the cumulative activity increased with increased cognitive load for some of the trunk and shoulder muscles examined. In addition to these metrics, further proof of cognitive motor interference was apparent through observation of participants. Participants slowed their movement while under the cognitive load, especially for the higher cognitive load condition. These observations suggested a prioritization of the cognitive task over the motor task. In particular, participants needing to stop their movement entirely suggested an internal need to switch from simultaneous processing of a task to serial processing due to the insufficient resources available to complete both tasks simultaneously. This over allocation of resources to the cognitive task (and subsequent under-allocation of resources to the motor task) indicated a cognitive dual-task effect on the motor task. This behavior aligns with properties described in the bottleneck processing model. In fact, for the higher cognitive load condition for nearly all subjects, this was the most common processing technique. In the simple cognitive load condition however, demands were less intensive resulting in an improved ability to allocate resources simultaneously to both tasks similar to that described in the central capacity model. Participants were able to complete these arithmetic questions, which involve internal interfering factors that share complex neural networks with that of movement, and the motion task simultaneously with minimal interference. Resources were divided between the cognitive and motor tasks while they were performed simultaneously. These observations suggest that processing techniques may dynamically shift as a function of task difficulty. Increasing the number of cognitive task difficulty levels can further explore this dynamic.

While the switching of techniques was likely utilized as a technique to compensate for overwhelmed processors, it does not completely eliminate the effects of the dual-task. Davis et al. (2002) observed a significant increase in spine compression in response to complex mental demands even before a lifting task occurred, although increases were modest. In addition, the observable effects seemed related to an individual's arithmetic skill wherein those more comfortable with performing quick mathematics took less time and less effort than those who were not. These observations align with the prioritization factors theorized by Yogev-Seligmann et al. (2012). Further research is needed to elaborate on the factors that contribute to an individual's ability to manage cognitive load especially in dual-task conditions.

5.2 Limitations

The most relevant problem that the researchers faced was ensuring that participants completed the cognitive and dual-task simultaneously. While simultaneous processing is impossible to completely control, its handling has been considered greatly and a few strategies were utilized to encourage its use in this study. The cognitive loading task (both simple and more challenging variations) were selected so that they were engaging enough to occupy the subject's mental processing while being simple enough to be completed within the time frame of the physical task. A series of pilot studies were completed to assess cognitive tasks that had face validity and conformed to the study goals. The cognitive loading task's aim was to keep the participant engaged enough to split their mental resources between the movement task and the cognitive task but not so engaged that it deliberately debilitated the motion of the participant. As an example, one variation of the math task piloted was too difficult for the pilot subject such that they stopped their motion to consider the solution to the math equation, and then performed the physical task. This transformed the task from a simultaneous cognitive loading task to a serial task where the subject mentally processed the cognitive task first, then completed the physical task. While this behavior still occurred for some trials and participants in this study, its frequency was reduced with the current question format. This behavior was difficult to completely eliminate so other methods were adopted to encourage completing dual-tasks simultaneously. This included ensuring that participants did not answer the cognitive task before lifting the box and after placing it on the rack and the incentive system. The incentive system rewarded fast and accurate performance. The accuracy portion of the reward encouraged that the cognitive task be completed while the speed portion encouraged the entire dual-task be done as quickly as possible. The joint reward aspects promoted the simultaneous completion of the two tasks.

Another key limitation was the number and diversity of subjects included in the study. Data from 11 subjects were used in the analysis and only one participant was female. An increased number of subjects to improve statistical power is ideal, however as this was an introductory and exploratory study, twelve subjects were deemed acceptable for this purpose. Including only one female was another limitation and a consequence of the convenience sampling used in this study. Subjects were recruited from the Ohio State University Columbus campus through word-of-mouth and flyers. As this study was completed over the summer, fewer students were present and in turn, recruitment was challenging. Including more female participants would improve the generalizability of the results. Another limitation is that participants were recruited from the Ohio State University Columbus campus and as such may not have been representative of manual material handling workers. All of the participants were students and did not have manual material handling work experience. It is possible that lifting or processing behavioral differences may be present between a student population and a material handling worker population. Anecdotally, the general lifting behavior observed throughout the subjects in this study, regardless of age or sex, did not differ greatly. In addition, each subject was normalized to their individual performance capabilities by calculating muscle activity as %MVC and conditions were compared within each subject—the variance was compared across subjects.

Another limitation is the motion artifacts that were observed when analyzing the data. As described in **Section 3.8**, artifacts in EMG signals are expected and were observed and removed in the post-data collection processing. However embedded artifacts within the signals that were not explicitly obvious resulted in large and unusual normalized EMG values -- particularly in the low height conditions. The cause was theorized to be a result of subtle movement of the EMG sensors while performing fast movements that resulted in loosened contact with the skin. To reduce the effect of these artifacts, an exclusion criteria for the 90th percentile value was created that filtered the problematic values. A total of 78 out of 11,586 values were removed.

Another limitation during the analysis was the division of phases while processing the 90th percentile EMG data. To focus on the placement portion of the task, each of the EMG trials after normalizing were divided in half and 90th percentile values were extracted for the second half. While a random sampling of trials showed that the halfway point corresponded well with the completion of the left twist (which meant the 2nd half was purely the placement task), a precise division of the phases would have been preferred. This phase transition point was manually extracted for each of the motion capture files. This point was non-translatable to the EMG trials however because the motion capture and the EMG software were (slightly) asynchronously collected on separate computers. Extracting the phase shift point from the EMG data would also be very difficult to extract given the nature of the data. A future study would segment these data to have precisely identified phases.

5.3 Future Work

Future research directions that can be implemented in subsequent studies are presented below. Changes in the current study to improve the scalability and statistical strength can be made including increasing the number of study participants, balancing the number of female-to-male participants, including material handling workers, and including a wider range of ages in the study. Other study improvements include improving the data collection and data analysis process. As mentioned in the limitations section, motion artifacts were an issue for data from some of the participants. This issue can be addressed by using physically lighter electrodes, attaching the electrodes more securely on the skin, altering the motor task, or using an alternative EMG system. Another area of improvement is to strengthen the data analysis by properly partitioning the phases in the data.

Broader study design changes include an increased focus on describing the Dual Task Effect using the framework proposed by Plummer & Eskes, (2015). In this framework the interference effect of the cognitive task is described on the motor task and the motor task's interference is described on the cognitive task. Both interference interactions are examined and quantified. To be able to describe this relationship in this form, a redesign of the procedure is needed including reconsideration of the measures extracted and the interpretation of these measures.

Another change that can be made is a redesign of the cognitive load questions used during the dual-task. As mentioned in **Section 3.1**, arithmetic questions have many benefits, including ease of grading and its known ability to induce stress. An issue that does arise from this specific combination of cognitive and motor tasks is the disparity of the task. The cognitive task has limited relatability to the physical task for those performing the task. Time-based questions are representative of questions that may be seen in material handling workers, however the act of doing math while lifting rarely occurs. As such there is a processing cost of context switching between these two tasks. Participants must shift their resources back and forth between the lifting task and the math task. Due to the limited inter-context between the two tasks, a greater transition effort is required. For the cognitive load conditions in a future study, increasing the context-relatedness of the motor and the cognitive tasks will enhance the face validity and reduce overlapping effects from context switching. Additionally, the research can be expanded by observing and accounting for psychosocial factors, such as time pressure or job pacing.

Other future work directions include examining the effect of cognitive-motor dual-task in a naturalistic environment where dual-tasking is common (i.e. a distribution center) to compare how the effects differ in the naturalistic versus the laboratory environments. In addition, a sampling of the cognitive loads that are present for workers in this setting would provide further context to the factors that may affect the development of stress or pain.

Chapter 6. Conclusion

This study examined the impact of varying levels of cognitive and precision conditions on muscle activity and kinematics of the trunk and shoulders as subjects concurrently performed cognitive tasks and a motor task simulating a manual material handling task. As precision and cognitive workload increased, lower near-peak (90^{th} percentile) normalized muscle activity and angular velocities in the trunk and shoulders were observed for some muscles and joints. A significant increase in cumulative electromyographic activity was observed for the erector spinae and abdominal muscles with increased cognitive load complexity and task precision. These results identified a behavioral trend of slower movement caused by the concurrent mental load and physical precision requirements of the tasks. While this resulted in lower peak normalized muscle activity values and body segment velocities, participants were mechanically loaded for a longer time, resulting in larger overall muscle demands, which could possibly lead to more muscular fatigue being experienced when performing more complicated manual material handling tasks. Several studies examining the effect of dual-tasking have been completed, however the majority of these studies focused on gait metrics. This research contributed to the literature on the effects of dual-tasking for occupationally-relevant work. The results here help quantify effects of non-physical factors that can affect biomechanical loading which can help bring researchers one step closer to understanding the complex interactions between the mind and body that could exist as workers perform these dual tasks on a daily basis.

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Appendix A: Abbreviations

Table A.1: Segment velocities abbreviation definitions

Abbreviation	Meaning
trunkFlexP1	Trunk Flexion (Phase 1)
trunkFlexP2	Trunk Flexion (Phase 2)
trunkExtP1	Trunk Extension (Phase 1)
trunkExtP2	Trunk Extension (Phase 2)
LtrunkTwistP1	Left Trunk Twist (Phase 1)
LtrunkTwistP2	Left Trunk Twist (Phase 2)
RtrunkTwistP2	Right Trunk Twist (Phase 2)
trunkLatBendP1	Trunk Lateral Bend (Phase 1)
trunkLatBendP2	Trunk Lateral Bend (Phase 2)
LShFlexP1	Left Shoulder Flexion (Phase 1)
LShFlexP2	Left Shoulder Flexion (Phase 2)
LShExtP1	Left Shoulder Extension (Phase 1)
RShFlexP1	Right Shoulder Flexion (Phase 1)
RShFlexP2	Right Shoulder Flexion (Phase 2)
RShExtP1	Right Shoulder Extension (Phase 1)

Table A.2: Muscle abbreviation definitions

Abbreviation	Meaning
ADL	Anterior Deltoid- Left
ADR	Anterior Deltoid- Right
ERSL	Erector Spinae- Left
ERSR	Erector Spinae- Right
EXOL	External Oblique- Left
EXOR	External Oblique- Right
LATL	Latissimus Dorsi- Left
LATR	Latissimus Dorsi- Right
ABDL	Rectus Abdominus- Left
ABDR	Rectus Abdominus- Right

Appendix B: Significant Changes Tables

Table B.1: Significant Angular Velocity Means and Changes in Trunk and Shoulder Segments from Cognitive Workload Effect (Degrees per Second)

Angular Velocity Changes in Trunk and Shoulder Segments from Complexity Main Effect						
Phase 1						
	None	Simple	Complex	None -> Simple	None -> Complex	Simple -> Complex
TrunkFlex	77.7	60.8	48.9	-16.9	-28.9	-12.0
LtrunkTwist	61.2	54.3	44.1	-6.9	-17.1	-10.2
LShFlex	168.5	146	116.7	-22.5	-51.8	-29.3
LShExt	153.8	141.7	119.1	-12.1	-34.7	-22.6
RShFlex	181.8	151.5	123.3	-30.4	-58.5	-28.1
Phase 2						
High	None	Simple	Complex	None -> Simple	None -> Complex	Simple -> Complex
TrunkExt	67.5	60	43.5	-7.5	-24.0	-16.5
LtrunkTwist	48.3	39.5	34.6	-8.8	-13.7	-4.9
trunkLatBend	26.3	17.5	15.9	-8.8	-10.5	-1.6
LShFlex	26.3	17.5	15.9	-6.9	-24.9	-18.0
RShFlex	119.8	112.2	92.9	-7.6	-26.9	-19.4
Middle	None	Simple	Complex	None -> Simple	None -> Complex	Simple -> Complex
trunkFlex	5.7	7.1	12.2	1.5	6.6	5.1
trunkExt	32.9	29.1	23.7	-3.8	-9.2	-5.4
LtrunkTwist	45.9	44.1	31.4	-1.8	-14.5	-12.7
Low	None	Simple	Complex	None -> Simple	None -> Complex	Simple -> Complex
trunkFlex	37.4	38.4	49.9	1.0	12.5	11.5
RtrunkTwist	39.4	31.5	28.9	-7.9	-10.5	-2.6
trunkLatBend	27.9	24.6	21.6	-3.3	-6.4	-3.1

Table B.2: Significant 90th Percentile Means and Changes in Normalized EMG Values from Cognitive Workload Effect (% Maximum Voluntary Contraction [%MVC])

Change in 90th Percentile MVC values from Complexity Main Effect						
	None	Simple	Complex	None -> Simple	None -> Complex	Simple -> Complex
ADL	29.56	25.71	22.62	-3.85	-6.93	-3.09
ADR	41.71	38.61	34.14	-3.10	-7.57	-4.46
ERSL	31.4	30.92	26.98	-0.48	-4.43	-3.94
ERSR	30.06	29.98	25.05	-0.09	-5.01	-4.92
LATL	13.08	12.07	9.42	-1.01	-3.67	-2.65
LATR	17.02	15.98	14.35	-1.04	-2.67	-1.63
EXOL	10.60	8.73	7.06	-1.87	-3.55	-1.68
EXOR	13.26	11.43	9.11	-1.83	-4.15	-2.32
ABDL	2.78	2.51	2.40	-0.26	-0.38	-0.11

Table B.3: Significant Integrated Means and Changes in Normalized EMG Values from Cognitive Workload Effect (%MVC*Frames [1 Frame = 1/1000 Second])

Change in Integrated Values (%MVC*Frame) from Complexity Main Effect									
	None	Simple	Complex	None -> Simple		None -> Complex		Simple -> Complex	
ERSL	74077	79743	102084	5665	8%	28006	38%	22341	28%
ERSR	57959	63989	73735	6030	10%	15776	27%	9746	15%
ABDL	7634	7161	8722	-473	-6%	1088	14%	1561	22%
ABDR	9068	8974	12037	-94	-1%	2970	33%	3063	34%

Table B.4: Significant Angular Velocity Means and Changes in Trunk and Shoulder Segments from Precision Effect (Degrees per Second)

Angular Velocity Change in Trunk and Shoulder Segments from Precision Main Effect			
Phase 2			
High	Low	High	Low -> High
LtrunkTwist	44.05	37.52	-6.53
Middle	Low	High	Low -> High
LtrunkTwist	48.58	32.34	-16.23
LShFlex	99.33	71.78	-27.56
RShFlex	84.57	66.14	-18.44
Low	Low	High	Low -> High
trunkLatBend	26.70	22.73	-3.97
LShFlex	113.87	93.36	-20.51
RShFlex	113.16	91.90	-21.25

Table B.5: Significant 90th Percentile Means and Changes in Normalized EMG Values from Precision Effect (% Maximum Voluntary Contraction [%MVC])

Change in 90th Percentile MVC values from Precision Main Effect			
	Low	High	Low -> High
ADL	27.74	24.19	-3.56
ADR	41.26	35.05	-6.21
ERSL	32.00	27.54	-4.46
ERSR	29.99	26.74	-3.25

Table B.6: Significant Integrated Means and Changes in Normalized EMG Values from Precision Effect (%MVC*Frames [1 Frame = 1/1000 Second])

Change in Integrated Values (%MVC*Frame) from Precision Main Effect				
	Low	High	Low -> High	
ERSR	60796	69659	8863	15%
LATL	27011	31141	4130	15%
LATR	29653	34280	4627	16%
EXOR	19828	23588	3760	19%
ABDL	7416	8262	846	11%

Appendix C: Non-Significant Figures

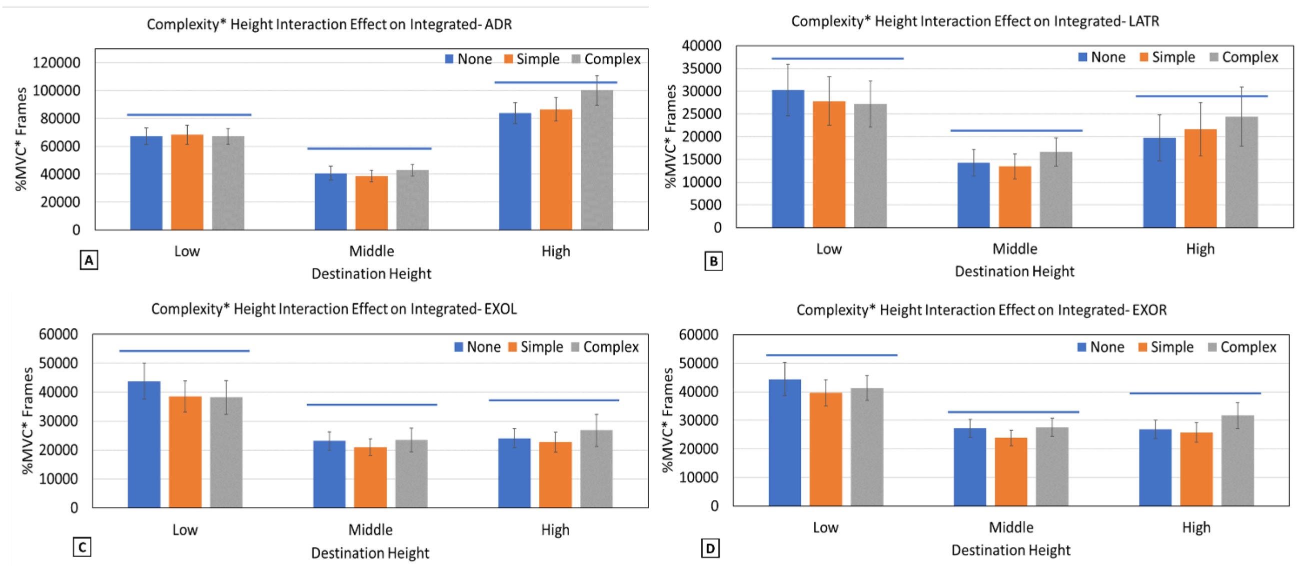

Figure C.1: Non-Significant Cognitive Workload*Height Interaction Effect for Integrated Normalized EMG Values for (A) Right Anterior Deltoid, (B) Right Latissimus Dorsi, (C) Left External Oblique, and (D) Right External Oblique. Note that integrated values were calculated by summing the normalized EMG value for each frame (where 1 Frame = 1/1000 Second). Horizontal bars that have different colors and positions between conditions represent statistically significant differences.

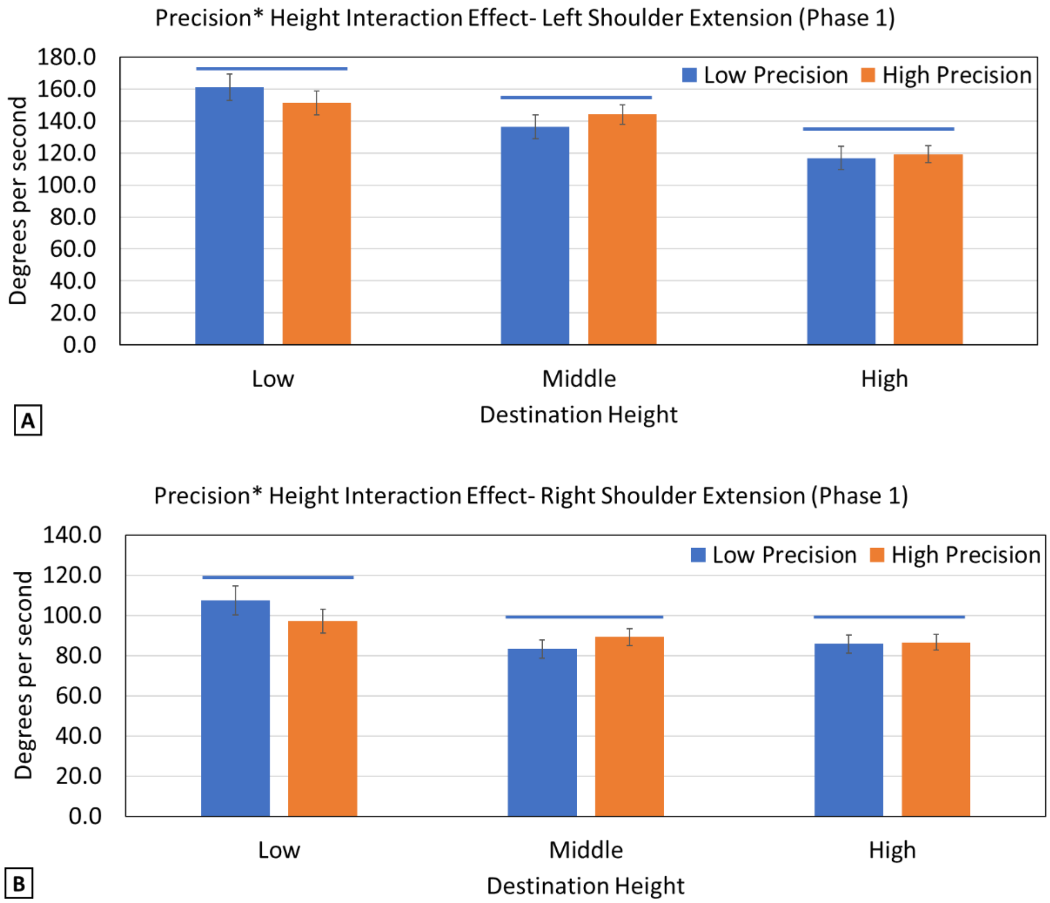

Figure C.2: Non-Significant Precision*Height Interaction Effect for Kinematic Measures (Phase 1) for (A) Left Shoulder Extension and (B) Right Shoulder Extension. Horizontal bars that have different colors and positions between conditions represent statistically significant differences.

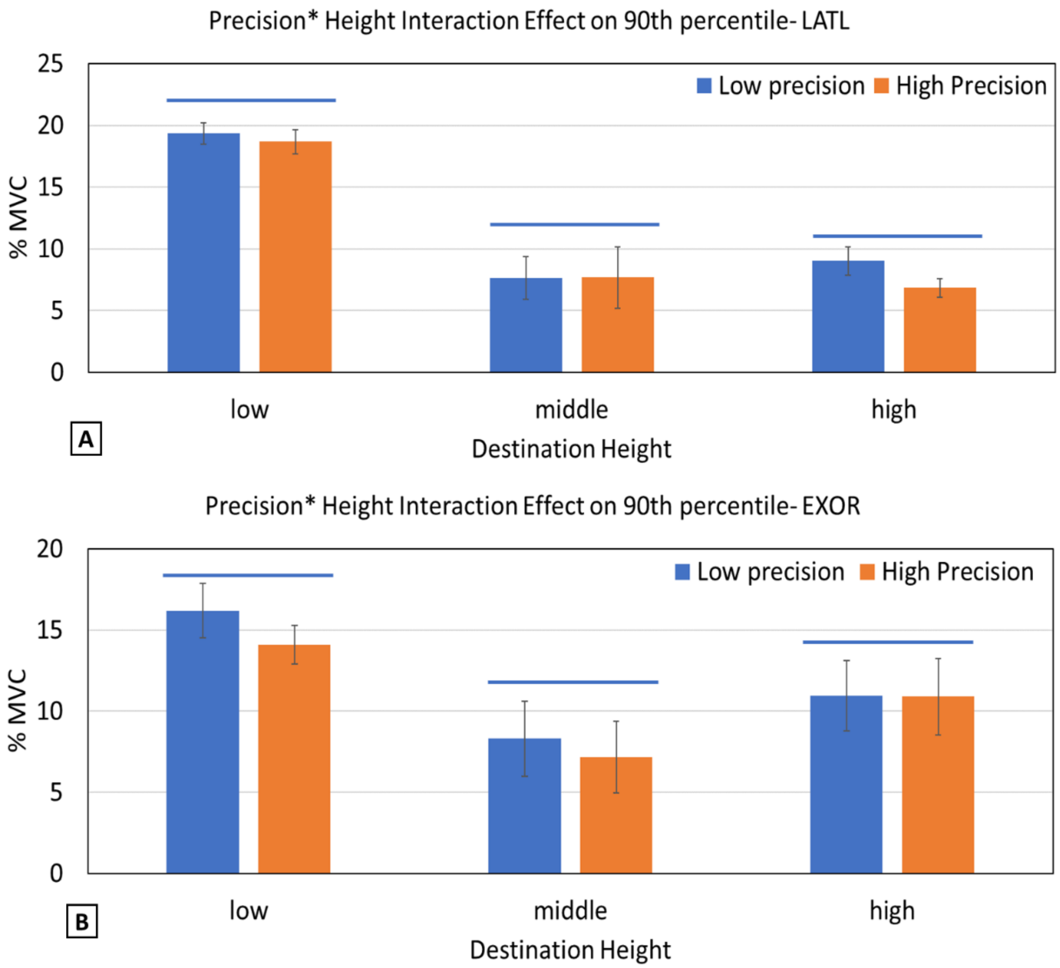

Figure C.3: Non-Significant Precision*Height Interaction Effect for 90th Percentile Normalized EMG Values for (A) Left Latissimus Dorsi, and (B) Right External Oblique. Horizontal bars that have different colors and positions between conditions represent statistically significant differences.

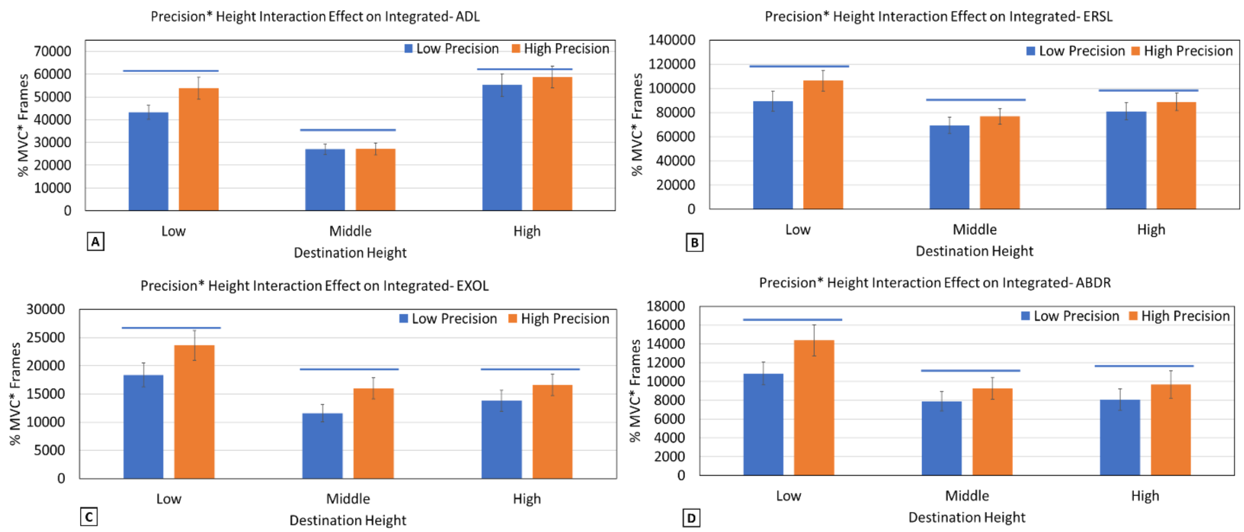

Figure C.4: Non-Significant Precision*Height Interaction Effect for Integrated Normalized EMG Values for (A) Left Anterior Deltoid, (B) Left Erector Spinae, (C) Left External Oblique, and (D) Right Rectus Abdominus. Note that integrated values were calculated by summing the normalized EMG value for each frame (where 1 Frame = 1/1000 Second). Bars that have different color and positions across conditions represent statistical significance.