Exploring the Utility of Inter-Segmental Coordination to Assess Movement Competency During Lifting Tasks

by

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Author's Declaration

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

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Abstract

Pre-employment screens are used within the hiring process to determine the hiring or placement of employees in the workplace. It is important that such screens adequately replicate or generalize to the work of interest. The objective of this study was to determine if individuals move similarly in the Epic Lift Capacity (ELC) test, a common pre-employment screen, compared to how they move when lifting during a long-duration work simulation, where movement was characterized as inter-segmental coordination. Twenty participants (7 males, 13 females) performed the ELC test, which uses a psychophysical approach to determine a participant's perceived maximum lift capacity, proceeded by a 90-minute work simulation.

Using motion capture data lumbopelvic, hip, and knee Relative Phase Angles (RPAs) were calculated using trunk and lower limb segment angles and velocities. The Mean Absolute Relative Phase (MARP) was calculated to quantify the overall coordination pattern of each joint in each trial, while the deviation phase (DP) was calculated to quantify variability in joint coordination within a trial. Measures of coordination were calculated and averaged over the first three lifts (initial lifts) and last three lifts (final lifts) of the 90-minute work simulation and were compared to the coordination measures associated with the lifts in the ELC test. Height (floor-shoulder, floor-knuckle, and knuckle-shoulder) and load (4.54 kg, and 75% of a participant's maximum) were controlled across conditions.

Results from this study show that when considering coordination broadly across all joints, coordination was most in-phase and least variable at the lumbopelvic joint relative to the more distal joints. Also, no differences were found between the ELC test and work trials at the lumbopelvic joint, suggesting that movement, at least about the lumbopelvic joint, was controlled similarly in the ELC test and simulated work trials. Considering the high incidence rate of lower back injuries in the workplace (Statistics Canada, 2014), investigation into the stability and coordination of movements at the lumbopelvic joint is of interest, and it is reassuring the lumbopelvic motion is similarly controlled in work as it is when performing the ELC. In contrast, at the hip and knee the coordination patterns were generally less in-phase (higher MARP) and showed more variability (higher DP) during the ELC test compared to both the initial and final lifts; however, differences at the knee appeared to be modulated by both height and load. In contrast, lumbopelvic joint coordination only changed between the initial and final lifts within the 90-minute simulation, as the final lifts were less in-phase than in the initial lifts. The coordinative changes seen in this study may reflect functional organismic and task constraint differences between the tasks.

Functional organismic constraints, such as fatigue or boredom may have resulted in coordinative changes over time in the work simulation, whereas task changes, such as task goal or objective, may have resulted in coordinative changes in the ELC test compared to the work simulation. Due to these apparent coordinative differences with changes in the participant and task, movement may be influenced by psychological, physical, and environmental factors, acting as constraints by altering movement outcomes (Glazier, 2017; Newell, 1986). These constraints may be important to incorporate into the future design and use of pre-employment screens when movement strategy is of importance, as changes in coordination did occur in this study, with small changes in objectives or over time, despite identical structural environmental design.

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GPT……………………………………………………………General predictive tests

TPT……………………………………………………………Task-related predictive tests

TST……………………………………………………………Task simulation tests

ELC……………………………………………………………Epic Lifting Capacity

DST……………………………………………………………Dynamic Systems Theory

MMH…………………………………………………………..Manual Materials Handling

FMS……………………………………………………………Functional Movement Screen

FCE ……………………………………………………………Functional Capacity Evaluation

RPA.…………………………………………………………...Relative Phase Analysis

RPL.……………………………………………………………Rating of Perceived Load

1.0 Introduction

According to the Canadian Centre for Occupational Health and Safety (2017), Manual Materials Handling (MMH) jobs can be defined as any work that involves “moving or handling things by lifting, lowering, pushing, pulling, carrying, holding, or restraining” ((CCOHS), 2017). By fitting the task to the worker, features of the job like shelf heights or loads can be manipulated to reduce risks associated with MMH tasks. However, in some circumstances, changing features of the job may be too expensive or not feasible. When job demands are not easily modifiable, or when they do not explicitly exceed recommended thresholds for exposure, it is possible to instead fit the worker to the task. Job matching (Armstrong et al., 2001) offers a framework for assessing the match between a worker’s capability and the demands of the job. Using a job matching approach a worker’s ability to meet the demands of a job are assessed prior to employment or placement in a specific role to ensure they are placed into a job for which they are capable of performing. For example, job matching based on physical capabilities has been found to be beneficial in reducing MSD rates (Harbin & Olson, 2005; Scott, 2002), as the workforce is more tailored for the work; however, there are many feasibility and ethical considerations when applying job matching in the workplace.

Selective hiring or placement based on individual capabilities can have important ethical implications. For example, the application of a pre-employment screen to assess capabilities within a job matching model could limit job opportunities for select populations, as identified by gender, age or disability, where those individuals may exhibit capability profiles that are not well matched to a particular job. As MMH jobs can be physically demanding, selecting a workforce that can meet the demands of a job may include testing specific capabilities such as strength or endurance (Harbin & Olson, 2005; Kuruganti & Rickards, 2004; Legge, 2013), or performing medical assessments (Fadyl, McPherson, Schlüter, & Turner-Stokes, 2010; Legge, 2013; McGill et al., 2015; Serra et al., 2007) to establish potential limitations. Women (Kuruganti & Rickards, 2004; Payne & Harvey, 2010), older adults (Payne & Harvey, 2010), or those with disabilities (Serra et al., 2007) may have different attributes relative to males, younger adults, or otherwise healthy working-aged individuals. To minimize potential discrimination when applying job matching, it is important that pre-employment screens adequately test capabilities in a manner that resembles how those capabilities would be used when completing the work (Kuruganti & Rickards, 2004; Legge, Burgess-Limerick, & Peeters, 2013). To ensure that pre-employment screens do adequately test capabilities in a manner that closely replicates how those capabilities will be used to perform the work required, the job demands need to be clearly investigated and defined before creating or implementing pre-employment screens (Armstrong et al., 2001).

Ensuring that a pre-employment screen adequately replicates the job demands can be difficult. Work can be complex and include a large range of movement, load and skill requirements. Replicating work for the purpose of pre-employment screening can also be expensive. This is especially true in situations where the worker needs to be trained prior to performing the pre-employment screen, particularly in situations where the work requires some fundamental skills, or when the equipment is dangerous to use without training (Dempsey et al., 2000; Petit, Rousseau, Huez, Mairiaux, & Roquelaure, 2016; Pransky & Dempsey, 2004; Serra et al., 2007). Additionally, some jobs may have physical demands that require higher physical capabilities and thus may be dangerous to replicate in a screen, as an individual may not be capable of demonstrating the required capability and could become injured in the process. Therefore, when designing pre-employment screens, it is important to balance between similarity to the job and the safety of the worker tested. To aid in this balance, select tasks or features of the work can be extracted and tested independently (Frost, Beach, McGill, & Callaghan, 2015).

Capacity-based measures, such as strength, pace or fitness-related abilities, are often tested to determine if an individual has the physical capacity to meet a job's demands (Chan, Tan, & Koh, 2000; Mahmud et al., 2010; Serra et al., 2007). Measures of capacity (i.e. timing, load lifted, number of repetitions, etc.) can be quantified in pre-employment screens, where an evaluator can objectively identify those who meet or exceed the capability requirements and are therefore eligible for hire or placement (Payne & Harvey, 2010). However, identifying which capacity measures are the most relevant to test is difficult. Often tasks can be performed in different ways and performance can be affected by many factors (Chan et al., 2000). Even if job demands are accurately determined, using isolated short-duration capacity tests to predict one's ability to meet the demands of frequent and dynamic workplace requirements has not been well validated (Jones & Kumar, 2003). Perhaps the validity of these tests can be improved by not only ensuring that pre-employment screens appropriately test the correct capabilities, but also that their design elicits similar movements or behaviours to those observed in work. By enhancing a pre-employment screens' similarity to work, we may be able to improve the validity of pre-employment screens to adequately identify those who meet the minimum requirements to effectively perform in a given job.

Although many pre-employment screen are designed to evaluate an individual's capacity, kinesiologists routinely subjectively evaluate an individual's movement through "biomechanical observations and body mechanics" to determine their fitness for work (Sinden et al., 2017). If kinesiologists are making decisions surrounding an individual's fitness for work, as well as making determinations surrounding their future performance or potential for injury based on movement observations, these pre-employment screens are being used in a context outside of their intended purpose. If the field continues to move towards the use of movement assessment in addition to capacity assessment within these pre-employment screens as a predictor of injury or performance, it is important to first understand if the movements observed during pre-employment screens represent those movements used in the workplace. Additionally, before the link between movement behaviour and injury risk or performance can be made, we need to first understand movement and how it changes in an occupational and pre-employment screening setting. Therefore, it is important to first consider if today's commonly applied pre-employment screens even challenge workers to use movement strategies that might be consistent with those they would use in the workplace.

Understanding how behaviour differs in the workplace compared to a pre-employment screens is important if movement is of interest to those conducting pre-employment screens. The same individual may perform a task very differently under different motivational and psychosocial factors, despite similar physical and environmental constraints as seen in return to work screening (Knauf, Asih, & Pransky, 2014; Oesch, Meyer, Bachmann, Birger Hagen, & Vollestad, 2012; Pransky & Dempsey, 2004). Therefore, movement may be influenced by psychological, physical, and environmental factors, acting as constraints by altering movement outcomes (Glazier, 2017; Newell, 1986). If the intent of a pre-employment screen is to identify workers that are well matched for a given job, then such a screen should likely challenge workers to demonstrate their capabilities by applying a movement strategy that would be similar to that used in the workplace. Therefore, ensuring that pre-employment screens require workers to apply similar movement behaviour to those found in the workplace is an important step in validating the use of pre-employment screening within the job-match model.

Identifying methods to quantify movement emerges as a challenge. One method to characterize movement behaviour during a task in order to identify similarities and differences (within- or between-task) is through the dynamics systems theory (DST). Historically, the main purpose of DST is to explain pattern formation, which allows DST to be used in a large range of disciplines ranging from chemical pattern formation to molecular biology (Kelso, 1995). In biological structures, DST can be used to determine how patterns adapt to changes in internal and external conditions, as well as identify the stability or variability in a given pattern (Kelso, 1995). On a macro-organismic scale, DST can be used to describe oscillatory human movement, where different segments move rhythmically or at a common tempo, as seen in walking (Turvey, 1990). Intersegmental coordination is consistent with DST and may provide a paradigm to evaluate movement within the pre-employment screening context (Kelso, 1995).

Therefore, if the movement strategy, as quantified using theoretically relevant measures like intersegmental coordination, is similar when completing a pre-employment screen compared to when performing an actual job task, it would greatly enhance the validity of using pre-employment screens within a job match model, where validation is often a point of limitation (Jones & Kumar, 2003). Furthermore, if movement differs when completing a pre-employment screen compared to a similar work task, this would suggest that future screens should better replicate the workplace, and current screens should remain within their original intended use. This study will use intersegmental coordination as a metric to quantify movement strategies, where intersegmental coordination will be compared between performances in a common pre-employment screening test, the Epic Lift Capacity (ELC) test, relative to performance in a high-fidelity simulated work task.

1.1 Research Question

Primary Research Question: Does inter-segmental coordination differ when lifting during the ELC test, relative to when lifting during a high-fidelity simulated MMH job task among a sample of healthy university students without previous manual materials handling experience?

Secondary Research Question: Does inter-segmental coordination change over time when lifting repetitively for 90 minutes during a high-fidelity simulated MMH job task?

1.2 Hypothesis

There are three main hypotheses for this research:

1) Inter-segmental coordination will not differ between ELC performance and the initial lifts during a 90-minute simulated MMH task.
2) Inter-segmental coordination will differ between the initial lifts and the final lifts during a 90-minute simulated MMH task.
3) Inter-segmental coordination will differ between ELC performance and the final lifts during a 90-minute simulated MMH task.

1.3 Research Objective

The objective of this research is to determine if inter-segmental coordination patterns observed during the Epic Lift Capacity test are similar to the inter-segmental coordination patterns observed in the initial or final lifts of an occupationally relevant work simulation in a healthy student population.

1.4 Importance of This Research

This research serves as a form of validation for the use of the ELC test as a pre-employment screen. If the data support the hypothesis, and movement strategies are consistent between the ELC test and initial lifts, but change between the initial and final lifts in the 90-minute work simulation, it may indicate that movement in this pre-employment screen is more similar to movement in early work, but is less similar to movement later on in work, when the individual has practiced or become fatigued. However, if there is a difference in movement control between the ELC test and both initial and final lifts, this pre-employment screen may not adequately challenge lifters to move in a similar manner to how they might move in the workplace. Factors such as learning (Knauf et al., 2014), boredom (Cummings, Gao, & Thornburg, 2015; Matthews & Campbell, 1998), or fatigue (Forestier & Nougier, 1998; Gorelick, Brown, & Groeller, 2003) may influence work behavior during task performance, or shape and constrain movement behavior within the ELC test. The application of robust and validated pre-employment screening tools can enhance employers’ confidence when employing a job match model to identify those who are capable of performing the required occupational demands.

2.0 Literature Review

2.1 Pre-Employment Screens

Manual Materials Handling (MMH) work can be physically demanding, and may require workers to perform tasks at a fast pace, with high repetition, or in non-neutral body postures (Punnett & Wegman, 2004). In an attempt to limit the physical demands associated with MMH work, job redesign, pre-employment screening tools, or education and training programs can be used (Jackson, 1994). Although job redesign is an effective option for better aligning the work to workers' capabilities (Legge, 2013; Rivilis et al., 2008), this may not be feasible in certain jobs where the work is variable and obstacles may occur that are out of the employers control (i.e. military, movers, firefighters, paramedics, etc.). In these circumstances, pre-employment screens can be used to identify workers that can meet the demands of the job through selective hiring. These tests can be capacity-based, and test a wide or narrow range of physical characteristics; however, before these pre-employment screens are deployed, they should have high construct validity, and should meet legal review to prevent discrimination in the hiring process (Campion, 1983; Jackson, 1994).

A pre-employment screening test must prove to be predictive of occupational performance or it may be deemed as discriminatory (Harbin & Olson, 2005). The use of pre-employment screens to selectively hire employees can have legal and ethical implications, as testing for physical capabilities can discriminate against women, or those with disabilities or previous health issues (Jackson, 1994; Legge, 2013). Pre-employment screening that focuses on specific characteristics or physical characteristics can have legal ramifications as it affects a worker's employment and earning capacity (Serra et al., 2007). Specifically, medical screening is a type of pre-employment screening that hires based on current health or previous medical history and its relation to a worker's ability to perform the job. Although discriminatory hiring is prohibited against those with disabilities in Canada under the Canadian Human Rights Act (CHRA) (R.S.C., 1985, c. H-6), those who may have medical conditions but are not considered disabled legally are not protected and could lose employment opportunities based on medical screening (Serra et al., 2007). Additionally, despite increases in women applying for physically demanding jobs, more women are being excluded due to differences in physical capacity during the pre-employment screening process (Jackson, 1994). For example, in the late 1990s a pre-employment physical capacity test for the British Columbia Ministry of Forests first response firefighting team resulted in 65% of males and only 35% of females passing, which eventually resulted in a ruling of discrimination from the Supreme Court of Canada (Anderson, Plecas, & Segger, 2001). It has since become common practice that job matching based on physical abilities or characteristics must be evidence-based and should meet legal review (Jackson, 1994). Therefore, to reduce the potential of discrimination and increase test validity, pre-employment screens should replicate the work required as closely as possible by identifying the skills and abilities necessary for performing the job.

Designing an effective pre-employment screening tool to assess the capability of an individual to perform work safely is not a simple process. The first step in creating an effective pre-employment screening tool is to analyze the tasks and demands involved in the occupation, encompassing primary movements, as well as other critical infrequent tasks that are required for the job (Payne & Harvey, 2010). The components included in a pre-employment screen must be representative of the occupational job, as well as reliable, valid, quantitative, feasible, and safe (Payne & Harvey, 2010). An effective pre-employment screening screen should also be simple to use, causal, and well-structured (Armstrong, 2001). Furthermore, determining pass/fail screen cut-offs is difficult, as the pre-employment screen must be strict enough to limit the number of false positives (accepting an individual incapable of performing the work) but lenient enough to limit false negatives (rejecting a capable individual) (Payne & Harvey, 2010).

There are many different approaches to pre-employment screening. Generally, pre-employment screens can be categorized into one of three groups (*Figure 1)*: generic predictive tests (GPTs), task simulation tests (TSTs), and task-related predictive tests (TPTs); where GPTs are based on general movement or capacity, TSTs are based on criterion job tasks, and TPTs are considered a compromise between the two extremes (Payne & Harvey, 2010).

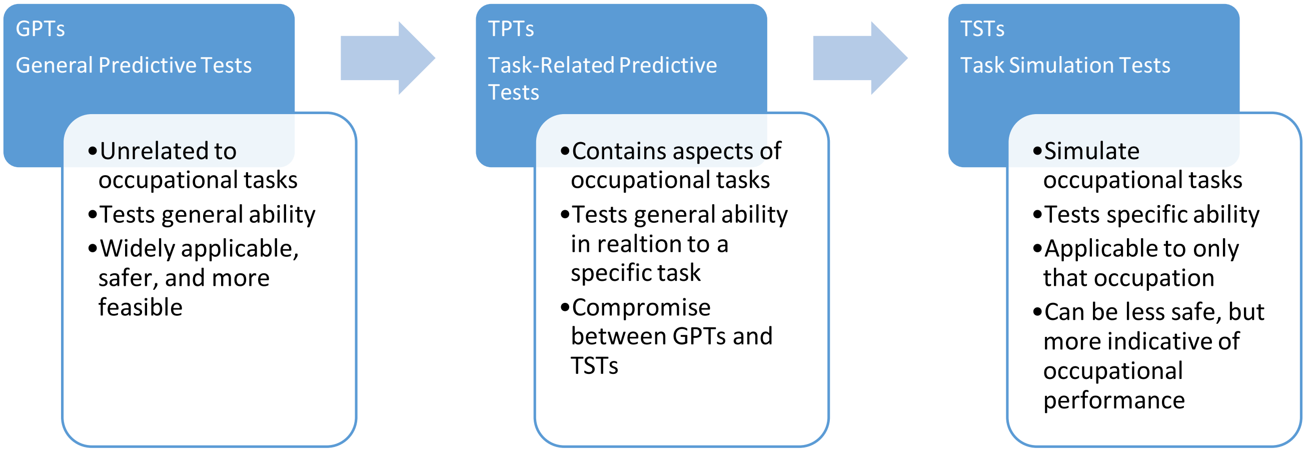

Figure 1 Categories of pre-employment screens (Payne & Harvey, 2010)

2.1.1 Generic Predictive Tests

GPTs are often used due to the simplicity of the tests' design and implementation. Since the movements are often familiar to the test administrators and workers, GPTs are viewed as relatively reproducible and reliable (Knauf et al., 2014). The testing of generic qualities such as fitness measures (i.e. grip strength) are common as they are considered more feasible and safer than replicating job tasks (Knauf et al., 2014). Testing on the basis of standard and often stationary fitness measures allows for a more controlled environment, reducing the risk of MSDs associated with reproducing physiologically demanding tasks (Jackson, 1994). Examples of fitness and motor ability measures that are tested with a GPT may include flexibility, balance, aerobic capacity, or endurance, as well as static, dynamic, and explosive strength.

The general features screened for in GPTs must prove to be highly correlated to job performance or demands (Knauf et al., 2014; Payne & Harvey, 2010). GPTs are often used due to the simplicity of set up, and the ability to generalize observed capabilities to many different tasks. More recently, the applicability of GPTs has come into question, as they can be seen as discriminatory if they do not directly relate to the work demands (Knauf et al., 2014; Payne & Harvey, 2010). As GPTs can be based on general physical capabilities, selective hiring based on these characteristics may prove to be discriminatory towards women or older adults if not directly related to job performance or safety (Harbin & Olson, 2005; Jackson, 1994).

2.1.2 Task Simulation Tests

TSTs are considered more accurate than GPTs at predicting work performance, as they test capacity in a manner that often replicates the real occupational task. Improved realism can lead to a higher degree of content validity (Knauf et al., 2014). Validity is especially important in physically demanding jobs where there is a large variety of required movements at a fast pace or high load, and where GPTs often cannot replicate the range of movements or the levels of physical demand. Examples of TSTs include: the York University occupation specific vision, hearing and fitness assessment for firefighters (Dunsmore & Hunter, 2000), Physical Abilities Requirement Evaluation (PARE) for municipal police officers (Dunsmore & Hunter, 2000), Physical Officer's Physical Ability Test (POPAT) for the RCMP (Royal Canadian Mounted Police) (Dunsmore & Hunter, 2000), and Physical readiness evaluation for police (PREP) for the

Canadian Armed Forces (Kuruganti & Rickards, 2004; Minister's Advisory Board on Canadian Forces, 1999). Some of the tests listed also include both GPT and TPT elements, such as pushing, pulling, lifting and carrying tasks; however, all government positions that require high capacity physically demanding work now include a TST component that replicates the job demands, such as obstacle courses, stair and ladder climbs, rope pulls, and person carries.

For a pre-employment screening screen to predict a worker's ability to perform work safely, the movement in the screen should replicate the movement found in the workplace. TSTs are more specific than TPTs, as TSTs mimic the work being tested for, while TPTs replicate more generic aspects of that work. A recent study compared TPTs including pushing, pulling, lifting, and lunging to firefighting TSTs such as chopping with a sledgehammer, forced-entry, hose drag, hose pull, and heavy drag, in a group of 52 firefighters (Frost et al., 2015). Despite the motions being similar between the two sets of tasks, the spine and knee range of motion used by participants when performing in the TPTs generally exceeded those used in the TSTs, suggesting the general tasks were actually more demanding (Frost et al., 2015).

2.1.3 Task-Related Predictive Tests

TPTs are often seen as a compromise between TSTs and GPTs, as they incorporate elements of work found in the occupational setting, but are often simpler, more feasible or safer (Payne & Harvey, 2010) than simulating an entire work environment. A TPT commonly applied by national corporations like CBI Workplace Solutions to support job matching is Matheson's EPIC lift capacity (ELC) test. Using a psychophysical approach, the ELC test has been found to assesses a worker's capacity to lift safely with adequate intra-rater reliability among healthy adults (Matheson et al., 1995), and considers the job demand requirements including: frequency, vertical lift height, lifting duration, and load lifted (Epic Rehab, 2016).

In general, the ELC test is an isoinertial test of lift-lower capacity that progressively increases loads and repetitions. This approach aims to test lifting capacity in a manner that also minimizes the risk of injury to the worker as they approach their maximum capability. A worker's maximum acceptable weight, or maximum, is tested in six subtests. The subtests determine a worker's 1-repetition and 4-repetition maximums at three lifting ranges: floor to knuckle height, knuckle to shoulder height, and floor to shoulder height. Using a psychophysical approach, the worker ultimately decides on their maximum weight, or the load that they feel that they could not lift more than 8-10 times in a typical workday. These self-imposed maximums may be affected by motivation, where workers may feel less inclined to push themselves past their physical limits; however, this likely increases the safety of the ELC test. The ELC test protocol is explained in depth in *Section 3.3.1,* with a visual outline of the protocol found in *Figure 7*, and the detailed Matheson ELC test instructions found in *Appendix A.*

Employers and researchers may choose to use the ELC test over other capacity tests due to the availability of a large age-stratified normative database including over 3,000 entries for working aged healthy females and males, providing a benchmark to compare their results. In a survey of kinesiologists' preferences in pre-employment screens (also known as functional capacity evaluation (FCE)) in Canada, the ELC test tied for the second most popular test where 12.2% respondents commonly used the ELC test as a pre-employment screening tool (Sinden, McGillivary, Chapman, & Fischer, 2017). The other second most popular test was the Work Well FCE at 12.2%, which also relies on a similar psychophysical-based paradigm for evaluating lifting capacity; however, the Work Well Systems FCE was found to be generally unreliable in a systematic review (Bieniek & Bethge, 2014). Although strength and load handling evaluations were found to have acceptable test-retest reliability at 96%, posture/mobility test-retest reliability, including dynamic squatting similar to that found in lifting, was lower at 67% and was deemed unreliable (Bieniek & Bethge, 2014). Lastly, although the Arcon FCE approach was the most commonly used (23.0%), it relies on a static strength testing paradigm, considered as a GPT approach. The ELC test was selected for consideration in this study due to its popularity as a TPT, the availability of a detailed protocol, its ability to be replicated in a work simulation, and general ease of use.

As such, the ELC test was selected as the pre-employment screen to be compared to the work simulation in this study. The ELC test allows the evaluator to test a worker's ability to lift loads at progressively increasing loads, between origins and destinations consistent with the actual work environment. This somewhat replicates the actual lifting associated with the job, but in a manner that can determine if a worker's maximum lifting capacity (i.e., load) is sufficient to meet the load requirements of the associate job. However, the ELC test requires that all lifts be performed in the sagittal plane (i.e. no asymmetry) and with a milk crate with horizontal handles. Considering the ELC test requires workers to lift in a manner that would be structurally similar to lifts in the work place (i.e., same lift origin and destination locations), this test offers the best opportunity to validate on the basis of movement strategy. If differences are found in the movement strategies employed between the ELC test and a simulated work task, we may be able to attribute those differences to the inherent features of pre-employment screening, rather than differences in generalizability between the pre-employment screen and work.

The ELC test, as a TPT, provides a standardized assessment of the capacity to lift; however, there are some limitations. The ELC test does not include any objective metrics to assess or score how individuals move when completing the required lifts. This is a concern as kinesiologists identify that subjective perceptions of "biomechanical observation and body mechanics" are often applied as criteria for ending an ELC test (Sinden et al., 2017), suggesting that one's movement in an ELC test may be predictive of the ability to move safely within the workplace. While it is straightforward to add objective metrics, it is first important to establish if movement behaviours demonstrated with a pre-employment screen like the ELC test are similar to movement behaviours demonstrated in the workplace. It is plausible that movement behaviours associated with lifting during the ELC test could differ from those used in the workplace, questioning the validity of evaluating "biomechanical observation and body mechanics" within a pre-employment testing paradigm. By exploring changes in movement behaviours between pre-employment screening and work, we can determine if lifting behaviours demonstrated in a pre-employment lift can be used to estimate movement behaviors in the workplace.

2.1.4 Capacity versus Movement Assessment

Currently, many commonly used pre-employment screens are based on capacity measures. These capacity-based tests may include maximum measures of strength, power, or speed. The aim of these tests is to quantify the capacity of potential employees, and compare those capacities with respect to the demands of the job. If the capacity of the worker exceeds the demands of the task, the worker is considered fit for the job. The general capacity based job-matching model is described in *Figure 2.*

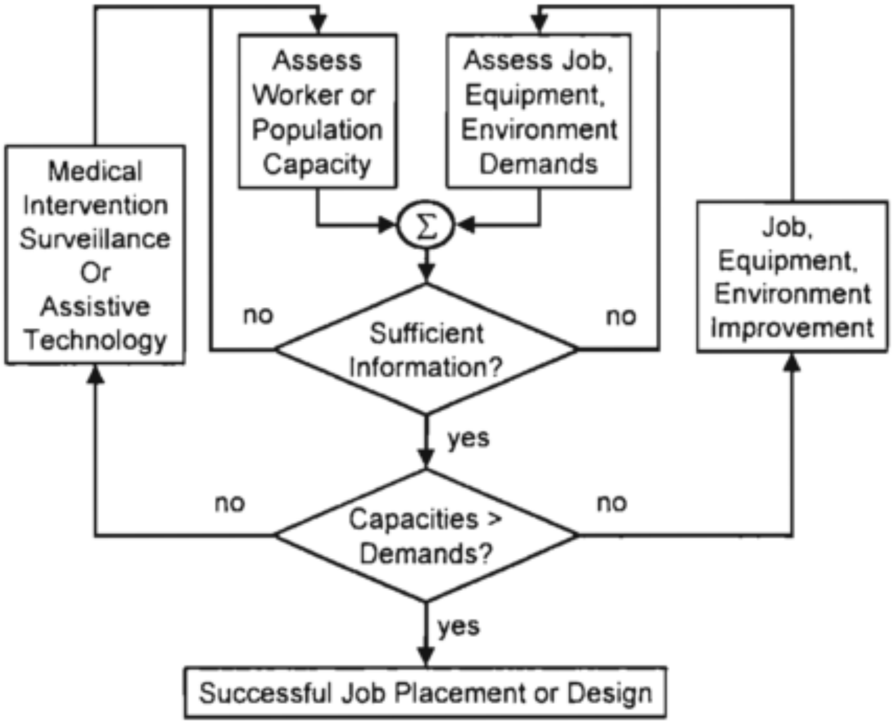

Figure 2 A capacity-based job matching model (Armstrong et al., 2001)

Many factors contribute to the link between work demands and workers' capacities, as depicted in *Figure 3.* To better match job demands and workers' capabilities, both the factors that influence undesirable responses, such as pain, injury, and fatigue, and those that influence desirable responses, such as health and safety should to be considered (Dempsey et al., 2000). Therefore, when utilizing capacity-based measurements in a pre-employment screening test, it is important to validate the connection between the capacity test and the work being screened for. However, as seen in previous research validating the Functional Movement Screen (FMS), which aims to test movement ability and coordination, performance in a task or athletic event can be independent of movement strategy (Beardsley & Contreras, 2014; Lockie et al., 2015; Parchmann & McBride, 2011).

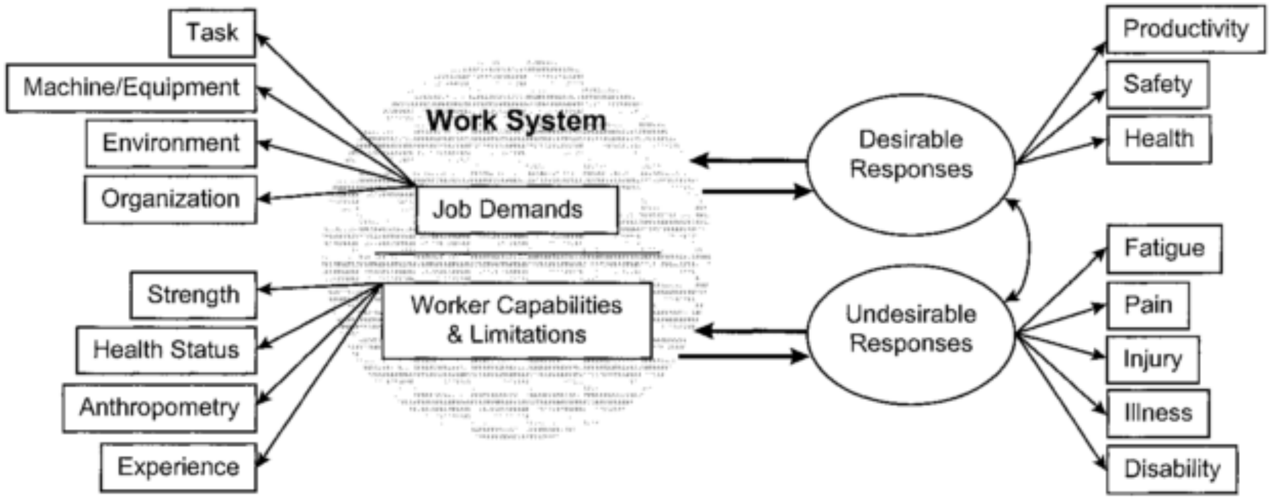

Figure 3 The relationship between job demands and worker capabilities (Dempsey et al., 2000)

Recently, the notion of assessing movement has gained popularity, particularly in an athletic or sport context, but may also be a valuable factor when considering links between capacity and job demands. Within sport, pre-season assessments have strayed away from pure isolated capacity measures, moving towards measures that consider movement competency, or the ability to perform functional movements efficiently (Cook, Burton, Hoogenboom, & Voight, 2014). Mapped to a pre-employment screening context, two individuals may be able to lift a 25 kg box, but could use a very different lifting strategy. Since pre-employment screens use capacity measures to predict future ability to lift loads, the ability of these pre-employment screens to predict future behaviour is often neglected. The workplace often involves complex and dynamics movements, therefore pre-employment screens should try to emulate these movements within the pre-employment screening process to better identify those capable of performing the tasks. Identifying differences in coordination patterns between pre-employment screens and work in similar environments, where the loads and height parameters are identical between the two tasks, could help determine the validity of using tests to predict behaviour in the workplace..

Movement assessment has been considered within a lifting context but is typically assessed using visual inspection. Quantifying lifting technique visually may be difficult as postures observed at the beginning of a lift are not always indicative of the technique used throughout the lift (Burgess-Limerick, Abernethy, Neal, & Kippers, 1995). As most individuals use a movement strategy defined as an intermediate between squat and stoop-like movements (Burgess-Limerick et al., 1995), differences between individuals and tasks may not be accurately defined with subjective observation. Additionally, posture changes through the course of a lift so summarizing lifting strategy using screenshots at one time point, such as at initiation of the lift, may not accurately depict the overall strategy used. Potential employees may have high capacity within a particular muscle group, but if they coordinate their movements differently in the workplace, and thus use contributions from different muscle groups, their predicted capacity might not infer well to the workplace environment. Therefore, it is important to consider how an individual coordinates their limbs to produce a movement within a pre-employment screen, and further, to determine if this coordination is consistent with movement behaviours demonstrated in work.

2.2 Features of Movement during Occupational Tasks

Many manual occupational tasks involve one or more of the following four tasks: pushing, pulling, lifting, and lowering. In a lifting context, different lifting strategies have been associated with increased risk of MSDs (Wai, Roffey, Bishop, Kwon, & Dagenais, 2010), and as such is the target of many studies and workplace interventions. Often pre-employment screening evaluations are based on visual inspection of movement or through the use of simple tools. This may lead to an oversimplification of movement, as even “simple” movement is complex and dynamic, and incorporates many moving parts (Wai et al., 2010). Therefore, the use of quantitative measures that can characterize movement can remove some of the observer bias that may occur in qualitative analyses.

2.2.1 Dynamics Systems Theory

One way to quantify movement is through the analysis of inter-segmental coordination. Analyzing the interaction between segments can help to quantify the roles of segments during complex movement (Burgess-Limerick, Abernethy, & Neal, 1993). Investigating inter-joint coordination, or the relationship between joints during movement, can involve both qualitative and quantitative analysis. Previously, maximum lumbar, hip, or knee flexion angles (Burgess-limerick, 2003; Plamondon, Delisle, et al., 2014; Splittstoesser, Davis, & Mamas, 2000), or maximum and minimum joint angles (Frost et al., 2015) have been used to quantify lifting technique or movement strategies. However, measures like inter-segmental coordination may be better to explain movement control as they have emerged from formative theories on motor control such as Dynamics Systems Theory (DST). Within a DST, theoretical orientation tools, such as relative phase dynamics, are available to explore the relationship between two segments' angular position and velocity throughout a task. This is advantageous over the use of time-discrete peak kinematic values, as the central nervous system is more likely to control synergies or relationships between segments as opposed to discrete kinematic parameters. Although DST can also use discrete measures to summarize coordination patterns and variability, these measures summarize entire cycles of movement, averaged across all time points. These tools are emerging as alternatives to using kinematic parameters relating to one time point alone, such as peak flexion angle, as a means to characterize movement strategy across an entire movement cycle or task, which is more consistent with prevailing theories of motor control. These more advanced tools may provide a better understanding of movement sequencing at each joint throughout the task duration, where this information may be helpful in identifying and improving movement behaviour.

Dynamics systems theory based methods are useful for detecting coordination patterns within a system. The mathematical framework has transitioned into identifying coordination and timing differences between segments, as seen in the early work of Von Holst (Von Holst, 1973) analyzing fish fin movement (Peters, Haddad, Heiderscheit, Emmerik, & Hamill, 2003). Relative Phase Analysis (RPA) has since been adapted to serve as an indicator of coordination patterns in occupational tasks, such as lifting (Burgess-Limerick et al., 1993; Scholz, 1993). An average coordination pattern can be identified from multiple trials of the same task, where the variability in coordination patterns can be compared between and within individuals to identify factors that affect the motor control of coordination (Nematollahi et al., 2016). Since movement is a complicated system of interacting parts, the degrees of freedom in this system can be reduced by learning a pattern that is functionally relevant for a given task (Glazier, Davids, & Bartlett, 2003). This supports the idea of “attractor” states, or a “default” movement strategies for a given movement, which is combined with other less frequently used patterns to create a flexible system that can adapt to different tasks or external changes while maintaining continuity and stability (Glazier et al., 2003).

One qualitative method for determining default coordination patterns and variability is through variable-variable plots. This can include angle-angle plots, which compare adjacent joint angles, or phase portraits, which compare the angle to the velocity of the same joint or segment throughout the cycle. An example of a variable-variable plot can be seen in *Figure 4a* (Fowler &

Goldberg, 2009). These plots can be compared between individuals for the same joint or segment, or between trials, to determine if the same pattern emerges between tasks or trials. A qualitative description of this relationship for one joint, which compares the angular displacement and the angular velocity of a segment or joint for one cycle can be seen in *Figure 4b* (Fowler & Goldberg, 2009).

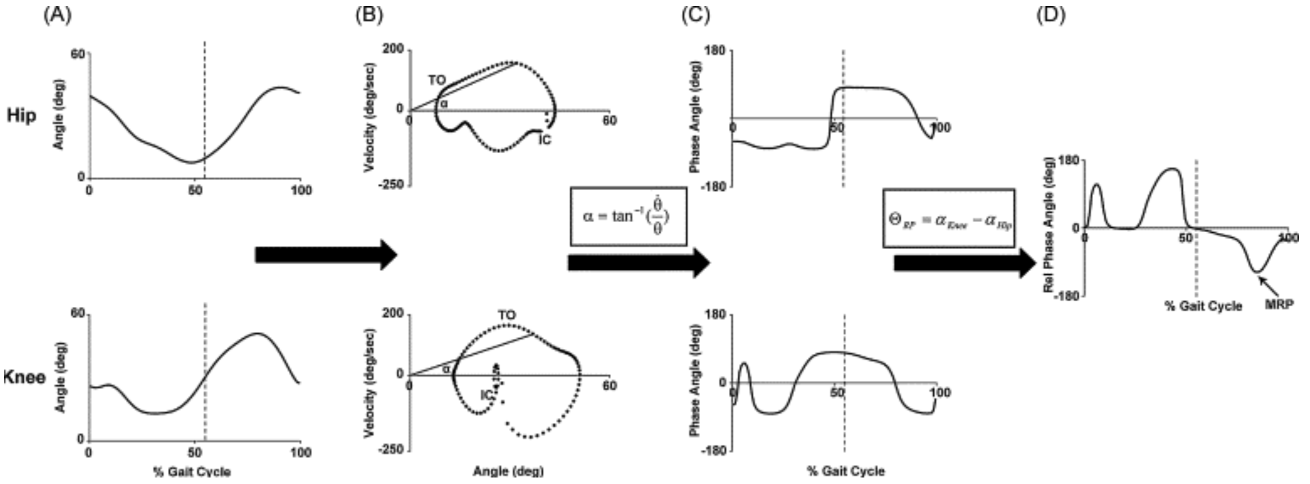

Figure 4 An example of the steps used for dynamics systems theory including the calculation of a) variable-variable, b) phase portrait, c) phase angle, and d) relative phase angle plots (Fowler & Goldberg, 2009)

By calculating the arctangent relationship between the angular velocity and displacement of a segment or joint (*Figure 4b*), the relationship between two adjacent joints or segments (i.e. hip and knee) can be quantified. This relationship between the velocity and displacement of a segment or joint is called a phase angle (*Figure 4c)*. The general calculation of phase angles is outlined in *Equation 1.*

Equation 1 Phase angle of a segment

$$\phi_{phase} = tan^{-1}\frac{\omega_{seg}}{\theta_{seg}}$$

Where ϕ is a phase angle, ω is the angular velocity, and θ is the angular displacement of a segment

To identify coordination patterns quantitatively, relative phase angles are produced by comparing phase angles of adjacent segments and joints (i.e. knee-hip relationship). The difference between the distal segment or joint's phase angle, and the proximal segment or joint's phase angle (*Equation*) is described as a relative phase angle (*Figure 4d*) (Fowler & Goldberg, 2009). Inter-segmental relative phase angles provide more information about the movement coordination between segments, as it contains information on the speed and direction of movement of each segment relative to an adjacent segment about the joint.

Equation 2 Relative phase angle of a joint (Stergiou, 2004)

$$\phi_{relative\ phase} = \phi_1 - \phi_2$$

Where ϕ is a phase angle, 1 is the distal segment, and 2 is the proximal segment

The use of continuous relative phase plots appears to give more information than kinematics alone, and are more sensitive to changes in movement strategies. For example, Nematollahi et al. (2016) reported no differences in discrete kinematics parameters, but significant and meaningful differences in relative phase coordination patterns between a sample of healthy and ACL-deficient patients when performing a box step-down and step-up task. Similarly, three years post ACL reconstruction, the use of kinematic parameters alone were not sufficient to detect differences between the post-surgery and control group in their gait kinematics; however, when using relative phase dynamics, there were clear differences found between the two groups in their coordination patterns (Kurz, Stergiou, Buzzi, & Georgoulis, 2005). Targeting lifting, kinematics alone have the ability to describe and differentiate movement; however, relative phase dynamics may provide more qualitative and quantitative information to describe lifting movement throughout the course of the lifting task (Lindbeck & Kjellberg, 2001).

DST methods have several benefits over a classical descriptive kinematics approach when trying to quantify movement during pre-employment screens. One benefit is the interpretation of relative phase curves when describing differences between tasks or trials. The slope of the relative phase curve provides information on movement coordination, where a positive value indicates that the distal segment is moving faster in relation to the proximal segment, and a negative value indicates the proximal segment leading the distal segment in movement (Kurz et al., 2005). A greater absolute relative phase value, closer to 180° or -180°, suggests an anti-phase relationship between two segments, and a value closer to 0° suggests a more in-phase relationship (Lamb & Stockl, 2014; Scholz & Kelso, 1989). An in-phase relationship depicts greater synchronization between the segments, as the two segments move in the same direction, whereas anti-phase segments move in opposite directions (Nematollahi et al., 2016). The minimum and maximum values gives us information on when a reversal or change in direction takes place, as one segment begins to move faster relative to the other (Kurz et al., 2005). For example*, Figure 5* depicts the relative phase plot for three inter-joint coordination patterns during a single lifting trial (Burgess-Limerick et al., 1993); however, contrary to more recent studies using DST, Burgess-Limerick and colleagues calculated relative phase angles as the distal joint phase angle subtracted from the proximal joint phase angle ($\phi_{relative\ phase} = \phi_{proximal} - \phi_{distal}$), and is interpreted as such.

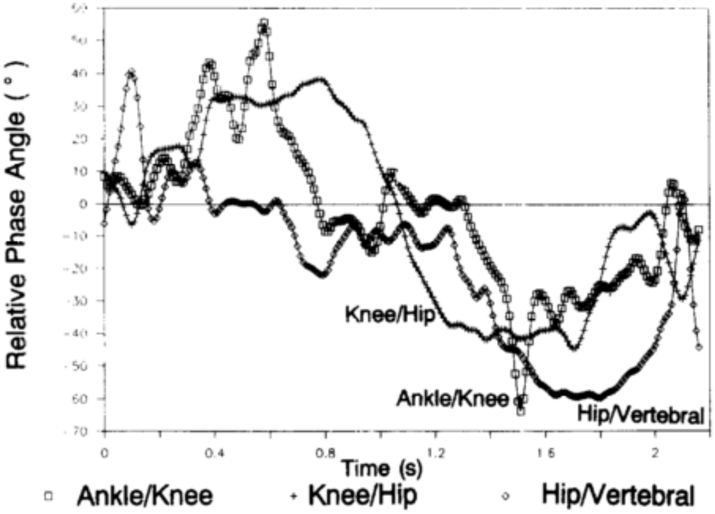

Figure 5 Relative phase angles of adjacent lower-limb joints during a single lifting trial (Burgess-Limerick et al., 1993)

Based on Burgess-Limerick and colleagues' calculation of relative phase angles, the first half of the *Figure 5* depicts the lowering or flexion phase to pick up the object being lifted (~1s). The positive relative phase value during this flexion phase depicts the proximal segments leading the distal segments during the descent ($\phi_{relative\ phase} = \phi_{proximal} - \phi_{distal}$). The maximum value during this period represents the point at which the distal segment begins to travel faster than the proximal segments. The second half of the lifting trial, the extension period, has negative values as the distal segments now lead the proximal segments. The minimum value in this phase represents the point where the distal segments start to lead less and proximal segments lead more. During both the lifting and lowering phases, the joint movement starts and ends in-phase with a value around zero, with much of the lifting movement being produced out of phase. (Burgess-Limerick et al., 1993)

Coordination can be quantified and compared using the Mean Absolute Relative Phase (MARP) and Deviation Phase (DP) metrics. MARP is used to summarize the coordination pattern between adjacent segments and can easily be compared between people, or between tasks within an individual. To calculate the MARP metric, first coordination is quantified as the relative phase between two segments for a given trial. Second, the absolute value for a relative phase curve is expressed (ARP) to simplify interpretation. Third, the mean of the ARP is calculated as the MARP. A larger MARP is indicative of more anti-phase coordination, as one segment is driving the movement or moving faster or further away from the other (Ghanavati et al., 2014; Kurz et al., 2005). MARP values closer to zero are indicative of a more synchronous in-phase relationship, as the movement in each segment is more similar to one another, and thus cancel each other out in the relative phase calculation (Ghanavati et al., 2014; Kurz et al., 2005). Complementing the MARP, the Deviation Phase (DP) expresses the standard deviation of an ARP, describing the variability in coordination within a trial. A higher DP value is indicative of less stability in intersegmental coordination, and a lower DP values suggest more stability in inter-segmental coordination within a trial (Ebrahimi, Kamali, Razeghi, & Haghpanah, 2017; Stergiou, Jensen, Bates, Scholten, & Tzetzis, 2001). The MARP and DP can be used to characterize the overall coordination pattern for a task, with trial-to-trial differences indicating adaptations due to external or internal factors, such as fatigue, or increased load (Scholz, 1993; Scholz, Milliford, & McMillan, 1995; Sparto, Parnianpour, Reinsel, & Simon, 1997).

2.2.2 Effect of Task Variables

Measures like MARP and DP appear to be more sensitive to detecting changes in movement strategies as a function of altered task characteristics, such as load, lifting height, and frequency, compared to classical descriptive kinematics approaches. An increase in load during lifting tasks results in a change in how individuals lift. When analyzing kinematics only, an increase in load during a lifting task from 9.1 kg to 18.2 kg corresponded to an increase in hip and knee angles by 4 degrees, and trunk flexion by 2 degrees, as well as increased hip abduction and trunk flexion velocity (Splittstoesser et al., 2000). When analyzing relative phase dynamics, a progressive increase in load from 2.5 to 10.5 kg in 2 kg increments also resulted in an increase in deviation from in-phase coordination, as well as a delay in relative phase minimums during extension for the hip-knee and lumbar-hip comparisons (Burgess-Limerick et al., 1995). Therefore, not only are DST measures sensitive to the changes in coordination explained by kinematic measures, but also provide more insight into the relationship between segments through the lifting cycle. While the discrete kinematic findings provide insight into peak postures, the coordinative measures from this study aid in understanding how these postures change with time, and how segments move in relationship to one another throughout the lift.

Changes in coordination pattern are more pronounced when lifting loads relative to a percent of the participants' maximum lifting capacity (MLC), i.e. relative loads. When the MLC was determined by the maximum load a participant can lift consecutively four times, there were continuous changes in coordination for the lower-limbs as the load increased from 15% to 75% MLC in 15% increments (Scholz, 1993). As relative load increased, the lumbar spine lagged further behind the lower extremity motion to produce a more distal-proximal pattern, as the knee extension lead back extension at a faster rate (Scholz, 1993). Similarly, when MLC was determined by maximum-effort lifting against a load cell, an increase in relative load from 15% to 75% also resulted in more distal-proximal lower-limb and torso coordination patterns, as the proximal segments lagged behind the distal, despite no significant changes in peak angles during the lifts (Scholz et al., 1995). Therefore, DST methods are able to capture differences in coordination that traditional methods were unable to capture. By taking both the speed and position of adjoining segments into consideration through the progression of a lift, an increase in lifting load results in a change in lifting technique, as quantified by relative phase dynamics.

Inter-joint coordination patterns are also altered in response to changes in both lifting origin and destination height. Changes in the final lifting height from the floor to waist or shoulder height results in significant alterations in trunk kinematics and ground reaction forces at the knee (Shin, Nance, & Mirka, 2006). Lifting origin also affects coordination, as lower lifting heights are associated with a more synchronous lifting pattern (Splittstoesser et al., 2000). This synchronization was based on a decrease in correlations between the hip abduction angle-trunk sagittal angle, sagittal hip angle-trunk sagittal angle, hip abduction angle-sagittal hip angle, sagittal hip-knee, knee angle-trunk sagittal angle, and hip abduction-knee angle as the lifting height increased (at 0 cm, 19 cm, 38 cm, 57 cm, and 76 cm from the floor) (Splittstoesser et al., 2000). The decrease in synchronized joint motion at higher heights may be due to an increase in trunk flexion, or a more stoop-like pattern at higher heights, as the trunk takes on most of the movement and load for the task (Splittstoesser et al., 2000). This shift to a more synchronous lifting patterns at lower lifting heights may serve as a protective mechanism, due to the increased peak L5/S1 resultant moments at lower origin lifting heights (Plamondon, Delisle, et al., 2014).

Fatigue is another factor that influences lifting movement, as jobs may require high repetitions without adequate rest. While lifting at 25% of maximum isoinertial force at a self-selected pace, a 31% reduction in power results in a decrease in overall joint range of motion, an increase in peak lumbar flexion angle, and an increase in hip-lumbar spine relative phase angle, suggesting a more distal-proximal pattern of lifting with fatigue (Sparto et al., 1997). This change in coordination may be an adaptation towards a less physiologically demanding pattern, placing less emphasis on the lower leg muscles to fight gravity, and increasing back extensor demand (Sparto et al., 1997). Other studies have found limited changes in coordination pattern with fatigue, suggesting that the inter-joint coordination pattern will resist change in order to continue the task movement, even with muscle fatigue (van Dieën, Toussaint, Maurice, & Mientjes, 1996). This suggests that coordination patterns are adaptable, and can change to maintain a consistent performance level despite fatigue. This discrepancy may be due to the type of activity used to fatigue. Intensive short-duration motor tasks, which included a back extension fatiguing protocol, led to a change in neuromuscular coordination but was not perceived as strenuous, while a generalized trunk and limb fatigue protocol resulted in no change in coordination pattern but was perceived as significantly more strenuous (Gorelick et al., 2003). As there appears to be a change in coordination pattern with specific types of fatigue, it is important to match the type of work practiced in the pre-employment screen to the occupational work, as tasks that may not appear strenuous can elicit changes in coordination patterns that may result in the worker becoming more susceptible to injury. In order to prevent fatigue, the pattern of movement adopted may be one that reduces muscular effort (Burgess-Limerick et al., 1995), or reduces injury (Kurz et al., 2005; Nematollahi et al., 2016).

The nature of the work may also contribute to changes in coordination. Monotonous and repetitive tasks, or tasks that require constant attention are often perceived as boring (Cummings et al., 2015). For example, studies on boredom are common in repetitive and unengaging work, such as assembly line work (O'Hanlon, 1981; Smith, 1981). Common coping strategies for boredom in the workplace is to produce task-unrelated thoughts, other task engagement (distraction), or change the task engagement (Cummings et al., 2015; Matthews & Campbell, 1998). Task-unrelated thoughts and distraction can potentially change how movement is performed, as the worker becomes less task-focused, or less focused on performance. Changing the task engagement can include imagining the task, refocusing, or changing the task, all of which may alter how the task is performed by changing the task goal.

2.2.3 Inter-Individual Differences

There are many factors that can lead to differences in inter-joint coordination between individuals. Specifically, age-related proprioceptive feedback changes can alter coordination patterns in older adults. When comparing younger adults (age: 24.7 ± 4.1 yrs.) and older adults (age: 71.6 ± 5.2 yrs.) during walking trials at self-selected, faster, and slower walking paces, older adults maintained a similar coordination pattern between all lower-limb joints at all three paces (Chiu & Chou, 2012). This is compared to the younger group, which significantly changed hip-knee patterns and increased variability (DP values) with an increase in gait speed (Chiu & Chou, 2012). Changes in lifting strategy have also been quantified, where older adults adopted a more leg-driven strategy (Shin et al., 2006), which may be due to relatively weaker trunk extensor muscles, and therefore less trunk stability in older adults compared to younger adults. This shift in control strategy may be a source of the reduced variability in coordination pattern found in older adults as reported by Chiu and Chou (2012), as older adults try to obtain stability through consistent, safer movements. This change in lifting strategy is conflicted by a study from Song and Qu (2014), which found an increase in hip flexion at the end of a lift with older adults. This suggests a more back-driven approach, despite starting with lower trunk flexion compared to the younger adults (Song & Qu, 2014). This discrepancy may be due to the lifting protocol between the three studies, with each protocol involving different lifting height, loads, and paces. Through the use of DST methods, it is possible to determine these age-related differences in movement strategy and variability that may not be possible with discrete kinematics alone. This apparent age-related reduction in the adaptability of coordination pattern to task variables may have consequences, such as altered ability to reduce fatigue, maintain balance, or prevent acute muscular injuries.

There are also sex-related differences in coordination patterns during lifting tasks. When compared to men, women's inter-joint coordination was more synchronous and had less variability when lifting 12.8 kg and 8.7 kg boxes from the floor to 61% of stature, or chest height (Lindbeck & Kjellberg, 2001). Although the 12.8 kg load may be relatively heavier for some women compared to the men, the increase in variability and the non-synchronous lifting pattern observed in the male group at heavier loads may be beneficial regardless of relative load, as it may reduce the muscular effort required by selecting the most efficient coordination pattern for the specific task (Lindbeck & Kjellberg, 2001). Similar adaptations are found to reduce muscular effort during lifting while approaching fatigue (Sparto et al., 1997). When comparing a group of manual materials handling (MMH) experienced female manual workers to both MMH experienced and inexperienced males, females displayed a more distal-proximal coordination pattern compared to the male groups with a greater delay between joint motions during lifting, leading to a less synchronous coordination pattern (Plamondon, et al., 2014). Due to a lack of comparison to novice females, it is unknown if women tend to adopt a distal-proximal coordination pattern in general, if the load was so heavy for the female workers that they adopted a less metabolically efficient pattern, or if this was a learned adaptation to MMH experience.

MMH experience also appears to affect coordination, as individuals experienced in manual lifting tasks tend to differ from novices in how they lift. When comparing those with 3-6 months of MMH experience (novice) to those with 6.5 to 33 years of MMH experience, the experts had smaller lumbar flexion angles and trunk inclinations than the novice group, as well as greater knee flexion during the lifting phase, when lifting from the ground (Plamondon,et al., 2014). This indicates the experts produce a more squat-like posture while lifting when compared to novices. These differences may need to be taken into account when implementing pre-employment screens, as learning or experience might alter initial movement patterns.

Since factors such as age, sex, or MMH experience can alter relative phase dynamics, it is important to consider these factors when investigating changes in movement behaviour. Although this study aims to compare within-participant differences in coordination pattern between the ELC test and a similar work simulation, it is important to consider confounding factors like relative load or shelf height that may change coordination independent of task or environment changes. As such, participation in this study included both male and female healthy university students, and was limited to those without MMH experience. Hopefully by controlling or limiting the effect of cofounding variables, differences in coordination or movement behaviour between the ELC test and work simulation can be attributed to task changes, rather than these individual or task environmental differences.

2.2.4 Intra-Individual Differences

Human movement requires control over an abundance of degrees of freedom to produce precise movements (Scholz, 1993). By organizing movement into synergies, a preferred pattern of movement can arise for similar movements, reducing the degrees of freedom required for a task (a classic definition for DST, as it applies to motor control). In order to produce a specific movement, such as a lift, the linking of multiple moving parts and the synergies that coordinate them need constant and specific feedback. The lower-limb in particular can be modelled as a kinetically linked system incorporating many moving parts (Apkarian, Naumann, & Cairns, 1989). To produce movement at a distal segment, movement must first be produced through sequential muscle activation in a proximal-distal sequence (McMullen & Uhl, 2000); however, this pattern often shifts to a distal-proximal pattern with familiarity with the movement and training (Gallahue, & Ozmun, 1995). Therefore, there may be a more efficient coordination pattern for a given movement, with limited degrees of freedoms and synergies. A large component to this coordination pattern is the feedback provided to the system, as proprioception can alter the timing of movement, the degree of muscular activation in different segments, and counteractions to perturbations (Ghez & Sainburg, 1995). As such, the pattern selected by individuals may depend on other factors such as experience or proprioceptive feedback, leading to variation in how individuals will perform a task.

Any number of factors can affect the movement strategy selected during pre-employment screening. Individual differences, such as lifting capacity, gender, and age, as well as environmental and task differences may contribute to changes in how individuals choose to control their degrees of freedom to obtain the task goal. In this study, the effects of these individual differences on coordination were controlled for using a repeated measures design and an exclusion criterion. To isolate differences in movement created by differences in task alone (pre-employment screening versus work), the structural task characteristics and environment, such as lifted loads and shelf heights, were controlled. However, it is thought that there are differences in coordination pattern between the ELC test and the final lifts in the work period due to inherent differences in fatigue, attention, and/or motivation. It is important to identify differences in coordination patterns between these task conditions to understand the utility and validity of using pre-employment movement screens to infer movement behaviours in the workplace.

2.3 Relevance to Current Research

Currently, there is a need for more valid and peer-reviewed assessment tools to predict work ability (Kritz, 2012). Ensuring pre-employment screens represent the work being tested for is crucial to both developing better pre-employment screening assessments and improving the targeting of training programs. By comparing movement strategy between the ELC test and a work simulation, we may be able to determine if the ELC test adequately replicates generic MMH work such that participants employ consistent movement strategies as characterized using coordination. Improving the validity of pre-employment screens is important and where validity is currently lacking (Jones & Kumar, 2003).

While many studies have compared kinematic features of movement in pre-employment screens and occupational tasks (Beach, Frost, & Callaghan, 2014; Frost et al., 2015; Lisman, O'Connor, Deuster, & Knapik, 2013), application of methods stemming from DST appear to offer a new perspective. Relative phase analysis is more sensitive to internal changes such as injury or fatigue, and external changes such as load, and lifting height. The analysis of inter-joint coordination patterns with DST may identify common movement features emerging between pre-employment screens and occupational tasks. Past research suggests there are key features in pre-employment screens, such as knee and lumbar angular maximum and minimum values, that can be generalized to occupation-specific tasks (Frost et al., 2015); therefore, there may be a link between the overall coordination pattern used in a pre-employment screening test and the pattern adopted for occupational tasks.

The studies that analyze inter-joint coordination often do so for a short duration or over a low number of repetitions, and in a very controlled environment, which may limit the individual's freedom to move "naturally" as they would in the workplace. By analyzing the participant over a longer period with limited instructions and more complex lifts at various heights and different loads, the occupational task becomes more realistic. The coordination pattern adopted during the initial and final lifts of a long shift could then be compared to the pattern adopted during the ELC test to determine if the pre-employment screening test is accurately predicting how the individual will move in the workplace. Identifying differences in movement or coordination between this screen and work will serve as the first step, where future work should try to link these coordinative differences with performance or injury implications in the workplace. Therefore, the purpose of this research is to identify if differences in coordination patterns in the ELC test emerged when compared to the initial and final lifts of a 90-minute simulated MMH task.

3.0 Methodology

3.1 Participants

Thirty-six participants were originally recruited for participation in this study. Ten participants were excluded due to previous MMH experience (n=5), injury (n=1), varsity athletic experience (n=2), and experience in biomechanics and ergonomics courses through their Kinesiology program (n=3). As a result, data were obtained from twenty-five participants. However, after collection, data from four participants were removed where: one participant's data were removed as they could not maintain the MMH simulation at the self-selected loads for 90 minutes, one participant was excluded due to errors by a volunteer in recording the lifted weight when the participant performed the work trials, and three participants data were not included due to technical difficulties with shelf sensors mid-collection, eliminating the ability to effectively determine the initiation and end of each lift. Although the original recruitment goal was eighteen male and eighteen female participants, challenges in recruitment limited the dataset to 20 participants (*Table 1*), including 13 females and 7 males.

On the basis of a priori power analysis (G*Power V 2.1.9.2), a minimum sample of 35 participants was required to detect significant differences in inter-segmental MARP values between task type (ELC, initial lifts, final lifts) with an effect size f(U) of 0.4 (estimated based on a partial $\eta^2 = 0.14$) using a three-way repeated measures ANOVA (α=0.05, 1-β = 0.8,). Actual or observed power and effect sizes are reported in *Appendix E-1* and *Appendix E-2.* For convenience, recruitment was primarily conducted through posters on the University of Waterloo Campus, with remuneration of up to $30 for participation.

Table 1 Participant Demographics

	Males (n=7)	**Females (n=13)**
Age (years)	20.9 ±1.6	24.2 ± 7.0
Height (m)	1.78 ± 0.09	1.63 ± 0.04
Weight (kg)	77.3 ± 12.7	66.5 ± 12.3

Prior to collection, participants were asked four questions to determine eligibility for the study (*Appendix B-2)*. Participants were asked via email if they had been injured in the past 12 months requiring rehabilitation or physiotherapy, their program of study, if they were a varsity or provincial level athlete, or if they had worked in a position where lifting, lowering, pushing, or pulling was their primary role. All students were given the opportunity to meet in person prior to collection, instead of answering the exclusion questions via email. Participation was restricted to those who had not suffered an injury that required physiotherapy or rehabilitation in the previous twelve months to minimize effects of injury or compensations on coordination. Participation was also restricted to those with less than 6 months of MMH experience to reduce the variability in coordination patterns that may be attributed to experience. Furthermore, those who were involved in university varsity or provincial/national-level athletics were excluded, as the participants would likely have received formal lifting training with high-level athletic teams. Lastly, kinesiology students were excluded, as they have likely learned about lifting technique or have some knowledge of biomechanics, providing them with a perception of “good” versus “bad” lifting technique, and may then alter their natural unobserved movement strategy to fit this prescription. Blinded consent was acquired prior to the collection for deception purposes, and full informed consent was acquired after the collection was finished and deception revealed. The study was reviewed by the University of Waterloo Office of Research Ethics Committee and received approval (ORE #: 21820) prior to recruitment and collections.

3.2 Instrumentation

3D kinematic data were collected at 60 Hz using an eight-camera Vicon passive optoelectronic motion capture system (Vicon, Centennial, CO, USA). The collection space was calibrated prior to participants' arrival. As outlined in *Figure 6*, the axis of the motion capture space aligned with the axis of the embedded force plates. The reported axis were consistent with ISB standards, where Y is directed upwards, X directed forward, and Z is to the right of the origin. The ELC test was performed in the positive Y, X and Z axes as shown, while the 90-minute work session was performed in the positive Y, negative X, and positive/negative Z axes. Since segment angles are calculated relative to the global axis and compared between tasks, the global axis was rotated 180 degrees about the Y axis for the 90-minute lifting trials in Matlab, prior to relative phase angle calculations.

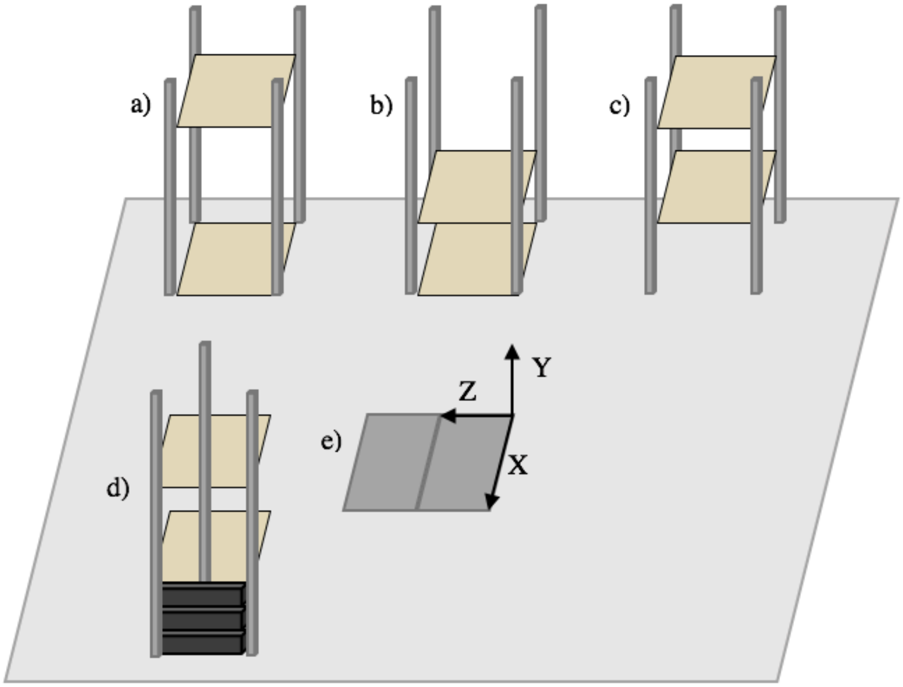

Figure 6 Laboratory set-up for the lifting tasks. The set-up includes three lifting shelves at a) floor to shoulder, b) floor to knuckle, and c) knuckle to shoulder heights, as well as the d) ELC test station, which also served as the instruction station. The origin of the space was placed on one of the two force plates (e), from which the global coordinate system is aligned

The collection set-up for the 90-minute work simulation is outlined in *Figure 6* and includes three height adjustable shelves for three lifting ranges: floor to shoulder, floor to knuckle, and knuckle to shoulder. The ELC test apparatus was also used as an instruction station across from the three lifting shelves, which provided the participants with instructions regarding the order of lifts. Voltage gated triggers were embedded into the three shelving units, where voltage data were collected at 960 Hz and synchronized with kinematics data to detect and isolate lifting events in the 90-minute lifting session. The ELC test apparatus was brought into the collection space prior to collection and removed after the conclusion of the ELC test. The ELC shelving unit had two height adjustable shelves and was structurally more robust than the 90-minute session shelves to handle more load.

3.3 Experimental Protocol

Participants spent 2.5-3 hours in the lab, during which time they performed a series of lifting activities while simulating a MMH work (stocking shelves), in addition to completing the EPIC lifting capacity test (ELC). The general study protocol is illustrated in *Figure 7.*

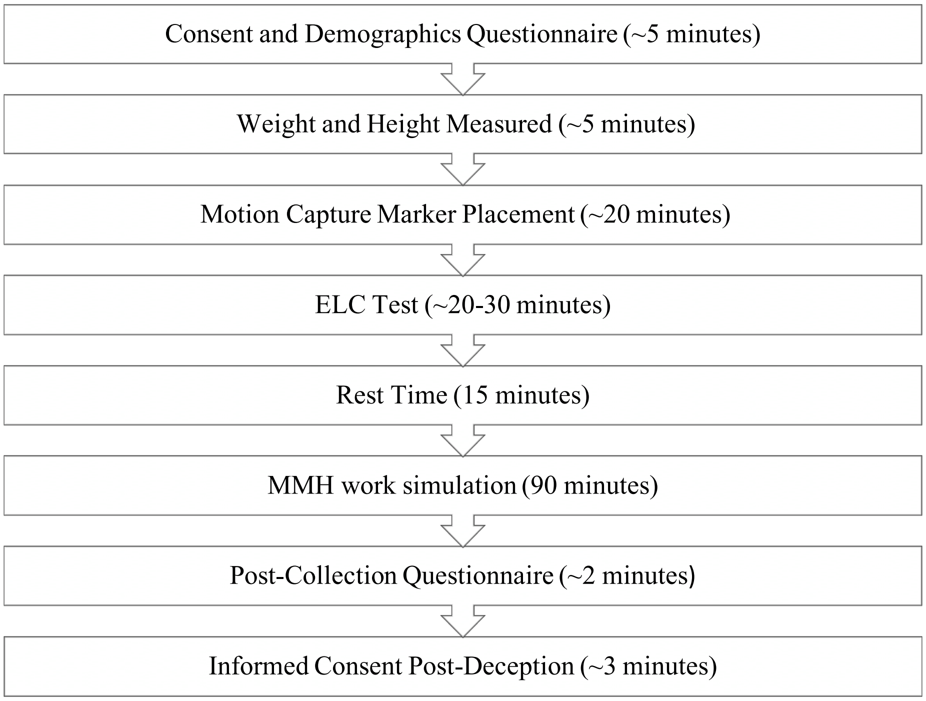

Figure 7 General protocol overview

3.3.1 Collection Protocol

Upon arrival to the lab, participants provided written informed consent, they completed a brief demographics questionnaire, and their height and weight was collected. The demographics questionnaire (*Appendix B-1)* allowed participants to give information about their age, sex, weight and height. Shelving heights were individualized, and were determined prior to collection by measuring the participants' knuckle and shoulder height, then subtracting the height of the box from base to handle (0.24m) to determine the appropriate shelf height. Therefore, during both the ELC test and MMH work simulation, the boxes handles would align with the participants' knuckle ('Knuckle') or shoulder ('Shoulder') height. Since the ELC test involves a box with handles that extend laterally from the milk crates' handles, different boxes were used in the MMH work simulation versus the ELC test, as this difference might be representative of differences between the ELC test and the workplace.

While two lab volunteers changed the various shelf heights to match the participants' anthropometrics, 35 passive reflective markers were placed on anatomical landmarks and used to define segment endpoints. Clusters of 4-5 markers were placed on the feet, shanks, thighs, pelvis, trunk, upper arms, lower arms, and hands and used to track segment motion during dynamic trials. An illustration of the marker and cluster locations can be found in *Figure 8*. A five-second static calibration trial was collected prior to the dynamic (task specific) trials, where the participant stood upright in the anatomical position to ensure all markers are visible and the static calibration trail was consistent across participants. The static calibration trial permitted the segmental motions (tracked via clusters) to be expressed relative to the segmental coordinate systems as defined by the anatomical landmarks. The ELC trial with the largest range of motion (Floor-Shoulder) was used as the dynamic calibration trial, so that the Nexus software could better track the relationship between segments during movement.

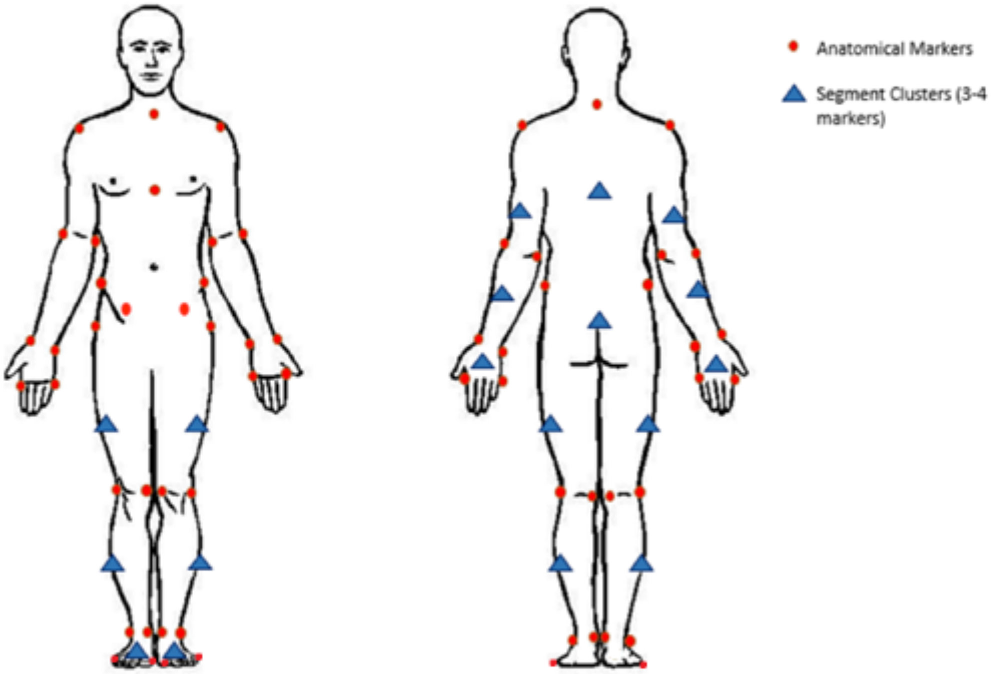

Figure 8 VICON Marker Placement

Once the participant was instrumented and the calibration trial was collected, each participant performed the ELC test. As pre-employment screens are used to selectively hire individuals fit for work, individuals would typically perform an ELC test prior to performing work. This was reflected in the study design, where participants always performed the ELC test prior to performing the work simulation. The ELC test was conducted as prescribed in the standardized instructions (*Appendix A)*. Six subtests are performed for the ELC test. Subtest 1 and 4 are performed at the knuckle to shoulder lifting range, subtest 2 and 5 are performed at the floor to knuckle lifting range, and subtest 3 and 6 are performed at the floor to shoulder lifting range. An overview of the ELC test protocol is described in *Figure 9*.

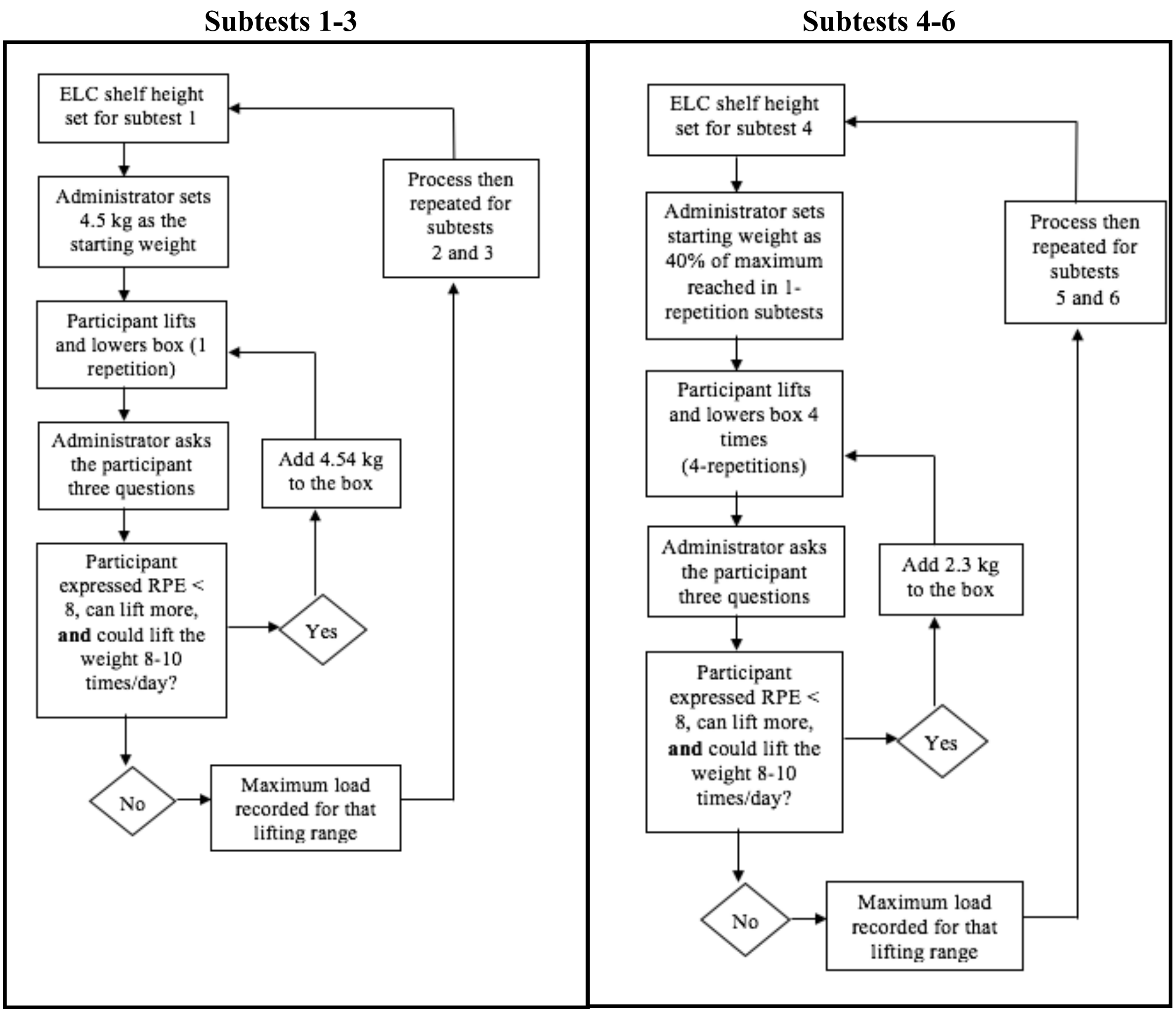

Figure 9 Overview of the ELC test protocol for subtests 1-3, which tests 1 repetition maximums, and for subtests 4-6, which tests 4 repetition maximums.

In all subtests, participants had one minute to complete the repetition(s), followed by a mandatory break. The break was a minimum of 1-minute but participants were encouraged to not start the next lift until they felt rested and ready, so this rest period was typically 1-4 minutes in length. The rest break was 2-6 times longer than the work period, which may be sufficient for a work period 10-30 minutes in length (Rohmert, 1973); however, we did not objectively measure fatigue in this study, so it is possible, though unlikely, that fatigue may confound the ELC test results.

After completing each lift, participants were asked for their Rating of Perceived Load (RPL), in which they rate the heaviness of the load from 1-10, as shown below (*Table 2).* If the participant responds with an RPL of 8 ("Very Heavy") or higher, the subtest is concluded, that load is recorded as the participants' maximum, and the next subtest is started.

Table 2 Rating of Perceived Load (RPL) (Epic Rehab, 2016)

Rating	**Perceived Load**
1	Like Nothing at All
2	Very Light
3	Light
4	Light-Medium
5	Medium
6	Medium-Heavy
7	Heavy
8	Very Heavy
9	Extremely Heavy
10	Too Heavy

If the participant rated the heaviness < 8, there are additional reasons a subtest could end. The participant was also asked "*Do you think you could lift this load 8-10 times per day*?" and "*Can you lift heavier*?". If the response to either question is "*no*", the subtest ends, and that load is recorded as the participant's maximum. If the response is yes to both questions, more weight was added to the box, and another lift is performed until the participant ranks the heaviness ≥8 or he/she answers "*no*" to one of the last questions to conclude the subtest. Additionally, the subtest was concluded if the participant exhibited 'dangerous lifting', as defined by the ELC test as using other body parts to support the box during lifting/lowering (i.e. knee, chest), or by having a stance closer than shoulder width without staggering their foot placement (Epic Rehab, 2016). The subtest was also considered completed if the participant reached 31.7 kg, as the ELC test box started to fail, and the participants started showing signs of ‘dangerous lifting’. In both the ELC test and work simulation, the participant was not instructed about how to lift the box, except for being told to use the lateral handles for the ELC test.

Following the ELC test, the participant had a mandatory 15-minute break before the MMH work simulation. The MMH work simulation (work trials) loosely resembled a shelf-stocking task to elicit “normal” lifting responses. The laboratory set-up (*Figure 6*) included three work stations to mimic three types of lifts seen in the ELC: floor to knuckle, floor to shoulder, and knuckle to shoulder. As previously stated, the shelf heights were based on the anthropometrics of the participant so that the handles aligned with the participants’ knuckles and shoulders. The participants first visited the instruction station, where instructions were provided regarding the order that participants would visit the lifting stations for each cycle, where all three lifting stations were visited in a randomized order each cycle. Once reading the instruction on station order (i.e. ‘1-2-3’, ‘3-2-1’, ‘2-3-1’, etc.), the participants visited each station subsequently to lift the boxes, then revisited the boxes in the same order to lower all three boxes (i.e. read instructions, lift boxes at ‘3-2-1’, lower boxes at ‘3-2-1’, return to instruction station). Collection began once the participant left the instructions station, and ended upon their return to the instruction station. Therefore, one trial contained three lifts and three lowers in a predetermined order. Separating the lifts and lowers allowed for the loads to be fully placed on the shelf sensors, and for the lifts to be easily isolated from the trial. The lifting and lowering order were randomized for each trial to reduce order effects, and to incorporate a cognitive aspect of the work that might be more generalizable to the workplace. As participants had to focus on the task and remember orders while performing tasks, the participants had to focus on the task as they would in the workplace.

While the participant was reading instructions, three laboratory volunteers changed the boxes loads, which were also presented in a randomized for each trial and participant. Randomizing the load order allowed the work to be variable, as it might be in the workplace, and to reduce order effects. The participants lifted boxes of three different loads: 2.3 kg, 4.5 kg, and 75% of their maximum. The 75% maximum was determined using the lowest 1 repetition maximum recorded during the ELC test. The two absolute loads of 2.3 kg and 4.5 kg were consistent across participants, where the 75% of the participants' maximum-based load provided a consistent and high relative demand for comparison. As a result, nine unique lifting actions were performed repeatedly at a self-selected pace during the 90-minute simulation (3 heights x 3 loads.

To meet the objectives of this thesis and to compare a more stable estimate of the participants' coordination pattern, only the first three lifts ("initial lifts") and last three lifts ("final lifts") of the work simulation at condition (load and height) were extracted for comparison to the equivalent condition during the ELC test lifts. Three trials were averaged so that the trials were far enough apart to get two distinct time points during the 90 minutes (initial and final), but enough to get a stable estimate of the participants' coordination patterns. With 20 participants, three trials should be a stable enough estimate of average movement strategy according to Forrester (2015), as well as Allread, Marras, and Burr (2000). Specifically, the 1-repetition at 4.5 kg during the ELC test was compared to the average of the first 3 lifts at 4.5 kg load during the work trial, and the average of the last 3 lifts at 4.5kg load during the work trial for each height condition. Additionally, at each height the 4-repetition ELC test lifts at the 75% maximum load were compared to the first and last three 75% maximum trials. For three participants, the 75% maximum load lifted in the work trials was not lifted in the ELC test, in which case the closest load within 4.5 kg was used for comparison.

3.3.2 Deception to Ensure Goal-Oriented Focus and Pacing

Although this study was designed to assess and compare movements, participants were deceived from this purpose. If the participants were not deceived, and told that the purpose of the study was to determine if workers move differently over time or between tests, they may alter their behaviour or become hyperaware of their movements, which could alter how they move in the simulation compared to outside a laboratory setting. Instead, by adopting a classic psychophysical framework, each participant was told that the purpose of the study was to estimate how many boxes a MMH worker should be able to move considering these prescribed task parameters (shelf height and box loads). Using a piece-work model, participants were told that they would earn 10 cents per box lifted up to $30 for the 90 minutes; however, the participants were encouraged to work at a pace that they could maintain for an eight-hour shift and still work the next morning without discomfort or fatigue. As there appears to be a proportional relationship between psychophysically acceptable and maximum voluntary forces, the participants were encouraged to maintain exertions equivalent to a score of 2 on a 0-10 Borg scale (Borg, 1990; Fischer, et al., 2012). Therefore, the participants were encouraged to balance being motivated to work hard to earn money but also to work at a pace that they could maintain for a long period of time.

The true purpose of the study was not revealed until the participants finished the collection and completed the post-collection questionnaire, where all participants received the same remuneration ($30). The instructors and lab volunteers gave no indication to the participants that technique was being evaluated, allowing the participants to focus on performing the task with limited external pressure to perform “well”. Instructors and lab volunteers allowed the participant to move as naturally as possible, allowing the participants to rest or work slowly if they wanted, and where participants were able to listen to music as they may be able to do during a work shift. The participants were also not aware of the time during the 90 minutes, as the participants might become motivated or discouraged by the length of time remaining, altering pace or effort. Instead, the participants were only informed as to when the 90 minutes started and ended. Combining minor deception with a long testing duration, participants may have been more likely to develop a natural rhythm, reducing concerns about being observed or critiqued on lifting form. While this cannot be validated, it is believed that this approach best encouraged participants to lift more closely to how they might lift during a MMH shift.

3.4 Data Analysis

The position data were visually inspected, re-labelled where necessary, and gap-filled using cubic spline interpolation up to 6 frames, pattern fills within a cluster, and rigid body fills when three other cluster markers were visible using Vicon Nexus 1.8.5 (Vicon, Centennial, CO, USA). Data was then exported to Visual3D V5 software (C-Motion Inc., USA) where a kinematic model for each participant was created, and segments were defined based on the anatomical landmarks described above. Using Visual3D, segment angles were calculated by expressing each segments orientation relative to the global coordinate system of the lab. Segment angles about the sagittal plane were extracted to describe the orientation of the thorax and hip, as well as the thigh and shank of the right leg.

Segment angles were exported into Matlab R2015a software (Mathworks Inc., USA) for further processing. The voltage data from the shelving sensors were down-sampled in Matlab to match the sampling frequency of the kinematic data (60 Hz). The voltage data were used to define lifting starting and ending points during the work trials. Approximately 100 ms, or 6 frames, were added on each end of the work lifting events, to capture any movement that prepared for or contributed to the lift slightly before and after the box was lifted on/off the shelf. In contrast, the ELC lifting start and end points were defined directly in Visual 3D by creating events using the local minimum and maximum forearm positions. The segment angles were exported in accordance with these events to ensure only the lifting cycle was analyzed. A lifting phase was defined as the movement of a box from a lower height to a higher height. The lifting segment angles were then dual pass filtered using second order low-pass Butterworth filter at a cut-off frequency of 6 Hz. Previous work by Makhoul et al. (2017) used residual analysis to identify that a cut-off of 4.4 Hz was appropriate when analyzing lifting motion. However, in that study Makhoul et al. tested experienced lifters, where this study explored novice lifters, who may demonstrate differences in their lifting actions. Therefore, 6 Hz was selected as a more conservative approach, remaining consistent with recommendations that human motion remains within 0-6 Hz (Winter, 2009). The segment angular velocity of each segment was calculated using the central difference method. Both the angular velocity and displacement for each trial was then time warped to 100 percent of lifting cycle using spline interpolation, in order to compare between trials (Fine, Likens, Amazeen, & Amazeen, 2015).

The method used to calculate relative phase angles was consistent with those suggested by Lamb & Stockl (2014). The angular displacement data were first centered about zero (*Equation* 3), then the data were normalized using the Hilbert transform method (*Equation 4)*. The Hilbert method has been shown to be the best normalization technique for non-sinusoidal signals since inter-segmental human movement is not a perfect oscillation, as the Hilbert transform method creates an analytic signal from a non-sinusoidal signal, removing frequency artifacts (Lamb & Stockl, 2014). Using this method, phase angles are only meaningful if the original signal is a narrow-band signal (Lamb & Stockl, 2014). Since the angular displacement during a lift occurs within a narrow frequency range of 0-6Hz (Winter, 2009), the data set satisfied this condition.

Equation 3 Centered angular displacement (Lamb & Stockl, 2014; Rosenblum, et al., 2001)

$$\theta_{centered,i} = \theta_i - \min(\theta) - \frac{\max(\theta) - \min(\theta)}{2}$$

Where θ is the angular displacement, and i is each time point from 1-100

Equation 4 Hilbert transform (Garbor, 1946; Lamb & Stockl, 2014)

$$\zeta = \theta_{centered,i} + H_i$$

Where θ is the angular displacement, H is the Hilbert transform, i is each time point from 1-100, and ζ is the analytic signal

The normalized segmental angles were then used to calculate phase angles. It is recommended that segmental phase angles be utilized in calculating relative phase angles for lower-limb human movement (Lamb & Stockl, 2014), as opposed to joint angles. Phase angles were then calculated by taking the arctangent of the segmental angular velocity divided by the segmental angular orientation at each point in each trial for each segment (*Equation* 5).

Equation 5 Phase angle of a segment using the Hilbert transformation and normalized angular displacement (Lamb & Stockl, 2014)

$$\phi_{seg} = tan^{-1}\frac{H_i}{\theta_{centered,i}}$$

Where ϕ is the phase angle of a segment, θ is the centered angular displacement of the segment, i is each time point from 1-100, and H is the Hilbert component or rate, throughout the cycle

The relative phase angles were then calculated by subtracting the phase angle of a proximal segment from the phase angle of the adjacent distal segment at each point in time, resulting in a relative phase angle between -180 and 180 degrees. A simplified version of the equation can be found in *Equation 2*, while an expanded version of the equation using the Hilbert transformation can be found below (*Equation* 6).

Equation 6 Relative phase angle calculation using the Hilbert transformation (Lamb & Stockl, 2014)

$$\phi_{relative\ phase} = \arctan\frac{(H_1\theta_2 - H_2\theta_1)}{(\theta_1\theta_2 + H_1H_2)}$$

Where ϕ is the relative phase angle between two segments, θ is the centered angular displacement, H is the Hilbert transform or rate, 1 is the distal segment, and 2 is the proximal segment

The process from angular displacement to relative phase angles calculation is highlighted using exemplar data as presented in *Appendix C*. Additionally, Relative phase analysis curves can be found for participant 8 at each height, load and task condition in *Appendix D-1, D-2, and D-3.* Four segments were used to create phase angles, resulting in three relative phase angles corresponding to each lift, as depicted in *Table 3*.

Table 3 Overview of relative phase angles, where α is the phase angle and θ is the relative phase angle for both the right and left side except for the thorax

Relative Phase Angle	Phase Components
$\theta_{\text{Lumbopelvic}}$	$\alpha_{\text{Pelvis}} - \alpha_{\text{Thorax}}$
θ_{Hip}	$\alpha_{\text{Thigh}} - \alpha_{\text{Pelvis}}$
θ_{Knee}	$\alpha_{\text{Shank}} - \alpha_{\text{Thigh}}$

Relative phase angle waveforms were reduced to two representative discrete parameters to compare between the work simulation and ELC test. The Mean Absolute Relative Phase (MARP) of the relative phase angles (*Equation 7*) was calculated as a measure of coordination about each joint during each lift, while the Deviation Phase (DP) was calculated to quantify variability in the absolute relative phase curve (*Equation 8*).

Equation 7 Mean absolute relative phase (MARP) (Ebrahimi et al., 2017; Galgon & Shewokis, 2016; Mokhtarinia, Sanjari, Chehrehrazi, Kahrizi, & Parnianpour, 2016)

$$MARP = \sum_{i=1}^{N} \frac{|Relative\ Phase_i|}{N}$$

Where N represents all trials (3 for initial and final lifting trials, and 1 or 4 for ELC test trials), and i represents all data points in each trial (1-100)

Equation 8 Deviation Phase Calculation (Ebrahimi et al., 2017; Mokhtarinia et al., 2016)

$$DP = \sum_{i=1}^{N} \frac{SD(|Relative\ Phase_i|)}{N}$$

Where N represents all trials (3 for initial and final lifting trials, and 1 or 4 for ELC test trials), and i represents all data points in each trial (1-100)

3.5 Statistical Analysis

Two 3-way repeated measures ANOVAs (α=0.05, β=0.08) were used to investigate differences in the Mean Absolute Relative Phase (MARP) and Deviation Phase (DP). Using SPSS software (IBM® SPSS®, 25.0, Armonk, NY, USA), three within-participant factors were considered in each ANOVA model including the primary factor of interest of task type (3 levels: ELC, initial lifts, and final lifts), in addition to the potential confounding factors of lift height (3 levels: floor to knuckle, floor to shoulder, knuckle to shoulder) and load (2 levels: 4.5 kg and 75% maximum). Three MARP and DP dependent measures were considered in the model: Lumbopelvic (representing coordination between the Pelvis and Thorax), Hip (representing coordination between the Thigh and Pelvis), and Knee (representing coordination between the Shank and Thigh) coordination measures. The dependent and independent variables for the MARP comparisons are summarized in *Table 4,* and the variables for the DP measures are found in *Table 5*.

Table 4 Outline of variables for the MARP three-way repeated measures ANOVA

Dependent variables	**Independent variables**		
Coordination pattern	**Lifting height**	**Load**	**Task (# of trials)**
Lumbopelvic MARP	Floor to Knuckle	4.5 kg (1 rep for ELC)	ELC test (1 or 4)
Hip MARP	Floor to Shoulder	75% maximum (4 reps for ELC)	Initial Lifts (3)
Knee MARP	Knuckle to Shoulder		Final Lifts (3)

Table 5 Outline of variables for the DP two-way repeated measures ANOVA

Dependent variables	**Independent variables**		
Coordination pattern	**Lifting height**	**Load**	**Task (# of trials)**
Lumbopelvic DP	Floor to Knuckle	4.5 kg (1 rep for ELC)	ELC test (1 or 4)
Hip DP	Floor to Shoulder	75% maximum (4 reps for ELC)	Initial Lifts (3)
Knee DP	Knuckle to Shoulder		Final Lifts (3)

A Bonferroni adjustment was used for the multiple comparisons in both DP and MARP measures. Sex was not considered in the statistical model, as we did not have the participant numbers to maintain power and conduct between-subject analysis; however, collecting both males and females helps to reduce sex effects in the sample. Interaction effects that included task and any main effects of task were explored, consistent with the objectives of this thesis. If height*task interaction effects were found at a given joint, a two factor (height and task) repeated measures ANOVA was performed after collapsing MARP and DP values across loads. Similarly, if load*task interaction effects were found for a given joint, MARP and DP values were collapsed across heights, and a two factor (load and task) repeated measures ANOVA was performed. Bonferonni corrections were used to isolate differences when main or interaction effects were uncovered. Sphericity was tested for all comparisons using Mauchly's test, and Greenhouse-Geisser corrections were used where sphericity was violated, as outlined in *Appendix E-1 and Appendix E-2.*

4.0 Results

4.1 Mean Absolute Relative Phase (MARP)

4.1.1 Differences with Task Type

There was a main effect of task type for all three MARP segment comparisons. Differences were found for the lumbopelvic (F(2, 38) = 4.151, $p = 0.023$, $\eta^2 = 0.179$), Hip (F(2, 38) = 19.106, $p < 0.001$, $\eta^2 = 0.501$), and knee (F(1.5, 28.47) = 5.414, $p = 0.016$, $\eta^2 = 0.222$) joints. As previously discussed in *Section 2.2.1*, a MARP value closer to 180 degrees indicates a more out-of-phase relationship between segments, whereas smaller MARP values, closer to zero reflect more synchronous in-phase pattern or more coordinative movement (Ghanavati et al., 2014; Kurz et al., 2005).

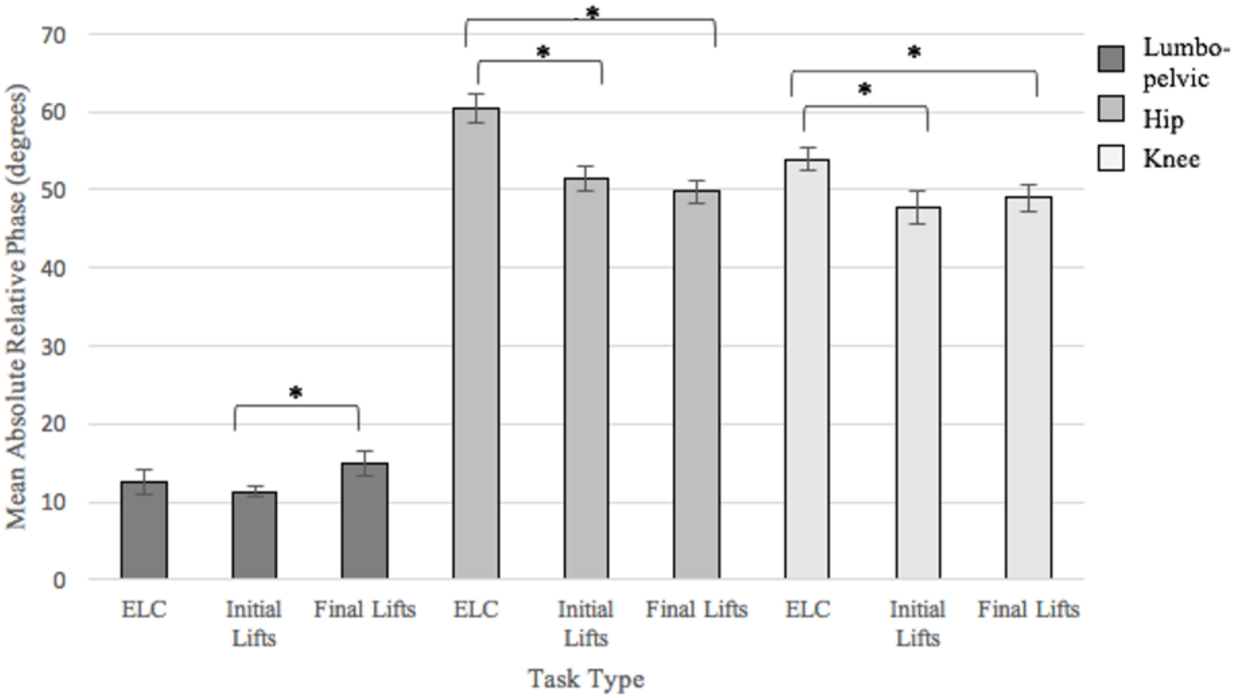

*Figure 10 Mean Absolute Relative Phase (MARP) angles between the ELC screen, Early Work, and Late Work for the three joints, where * indicates $p < 0.05$. Standard error bars are used to represent variance within the figure.*

As shown in *Figure* 10, pairwise comparisons indicated that lumbopelvic MARP was only different between the initial and final lifts during the work session, with the final lifts having a higher MARP than the initial lifts ($p = 0.017$). This contrasts the findings for the hip and knee joints, where there was no difference between initial and final lifts ($p = 0.811$ and $p = 1.00$ respectfully); however, differences were found between the ELC test and both the initial and final lifts for the hip and knee. For the hip joint, the ELC test had a higher MARP compared to the initial ($p < 0.001$) and final ($p < 0.001$) lifts. Similarly, at the knee joint the MARP for the ELC test was higher compared to initial ($p = 0.005$) and final ($p = 0.024$) lifts.

4.1.2 Interaction Effects

For MARP variables, there were both height and load interactions, with the exception of the hip joint, which had an independent task effect. For the lumbopelvic joint, there was a height*task interaction effect ($F(2.56, 48.73) = 3.54$, $p = 0.027$, $\eta^2 = 0.157$), suggesting the main task effect was modulated by height. For the knee joint, there was both a height*task interaction effect ($F(4, 76) = 9.58$, $p < 0.001$, $\eta^2 = 0.335$) and a load*task interaction effect ($F(2, 38) = 4.26$, $p = 0.021$, $\eta^2 = 0.183$), suggesting the task effects at the knee were dependent on both load and height conditions.

The height*task interaction effects are described in *Figure 11*. At the lumbopelvic joint, the ELC test MARP was lower than the final lifts MARP at the floor-shoulder height ($p = 0.008$), and the ELC test MARP was lower than both the initial lifts ($p = 0.005$) and the final lifts ($p = 0.003$) MARP at the knuckle-shoulder height. At the knee joint, the ELC test MARP was higher than both the initial lifts ($p < 0.001$) and the final lifts ($p < 0.001$) MARP at the floor-knuckle height, and the ELC test MARP was lower than the final lifts MARP ($p = 0.008$) at the knuckle-shoulder height. As a general observation of the interaction effects, the pattern of MARP values between tasks during the floor-knuckle and floor-shoulder were similar to the pattern of MARP values observed when considering the main effect of task; however, MARP values during the knuckle-shoulder lift were not similar.

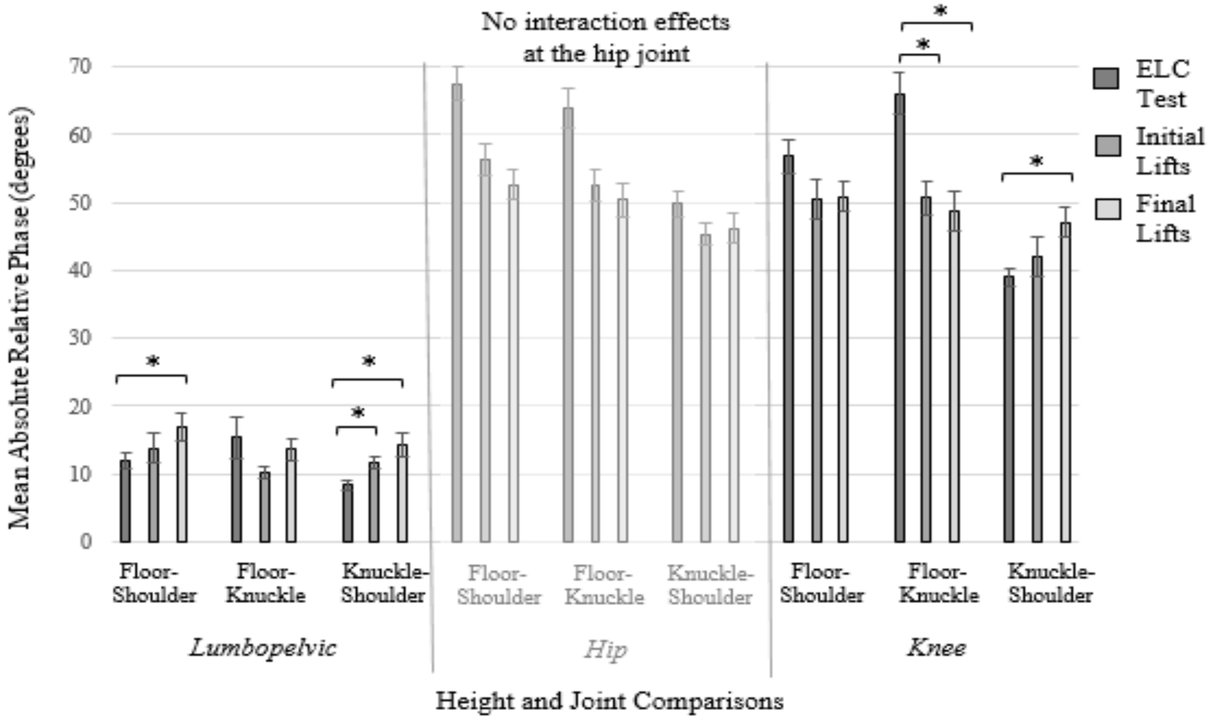

*Figure 11 MARP height*task interaction effects at each joint (Lumbopelvic, Hip and Knee) for each task type (ELC, Initial Lifts, and Final Lifts) and lifting height (Floor-Shoulder, Floor-Knuckle, Knuckle-Shoulder), where * indicates $p < 0.05$. Standard error bars are used to represent variance within the figure.*

Additionally, the load*task interaction effect can be seen in *Figure 12* for the knee joint. Specifically, the ELC test MARP was higher than both the initial lifts ($p < 0.001$) and final lifts ($p = 0.027$) MARP during the 4.54 kg load condition.

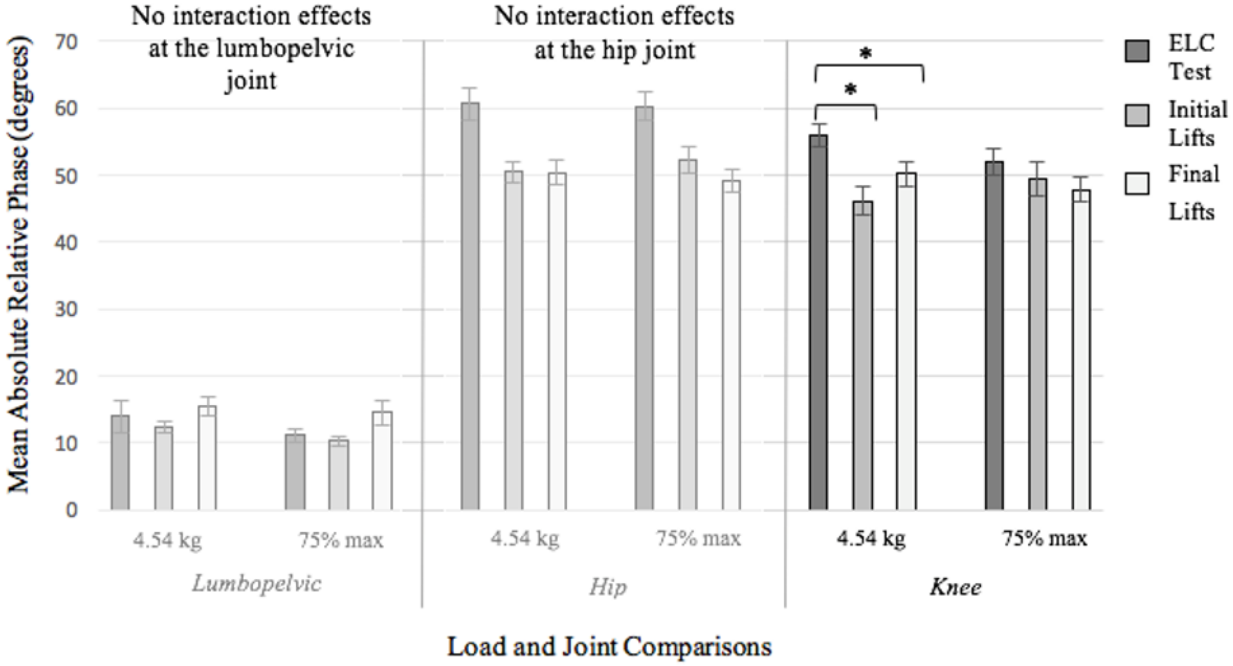

*Figure 12 MARP load*task interaction effects at each joint (Lumbopelvic, Hip and Knee) for each task type (ELC, Initial Lifts, and Final Lifts) and load (4.54 kg and 75% maximum), where * indicates p < 0.05. Standard error bars are used to represent variance within the figure.*

4.4 Deviation Phase (DP)

4.4.1 Differences with Task Type

There was a main effect of task type for both hip DP (F(2, 38) = 18.75, $p < 0.001$, $\eta^2 = 0.497$), and knee DP outcomes (F(2, 38) = 6.23, $p = 0.005$, $\eta^2 = 0.247$), as seen in *Figure 13*; however, there were no differences between tasks for lumbopelvic DP (F(2, 38) = 0.447, $p = 0.643$, $\eta^2 = 0.023$). Power, effect size, and sphericity values can be found in *Appendix E-2.* As described in *Section 2.2.1,* a lower DP represents more stability in the inter-segmental coordination pattern within trials, while a higher DP indicates more variability in the pattern (Ebrahimi et al., 2017; Stergiou et al., 2001).

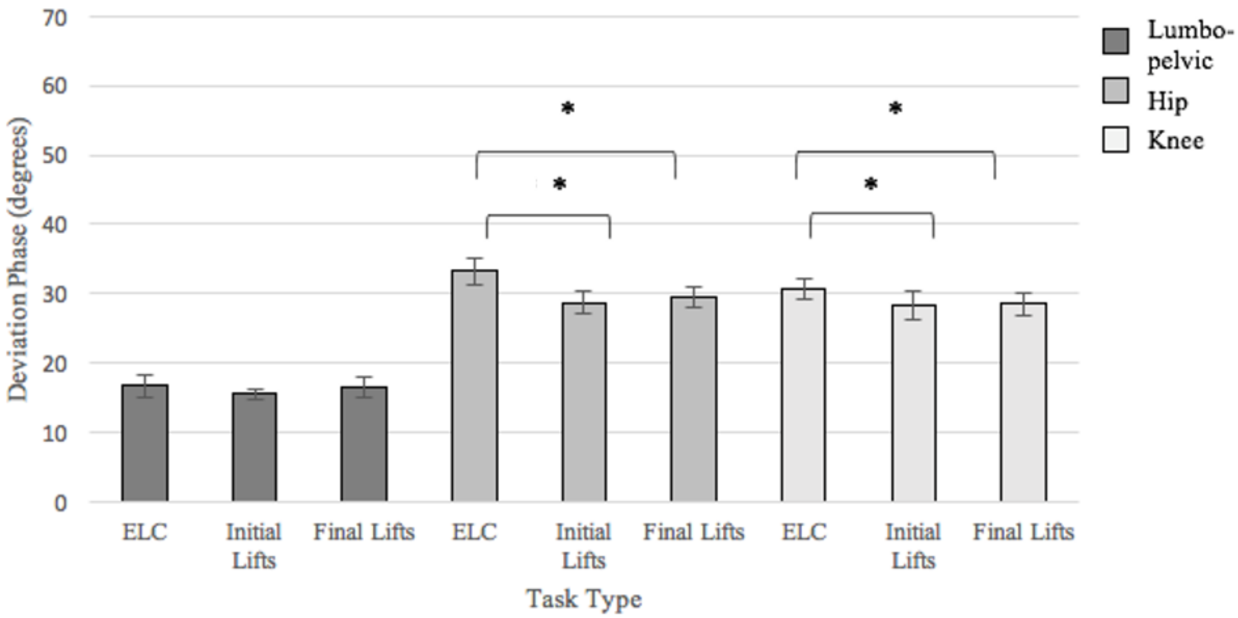

*Figure 13 Overall Deviation Phase (DP) angles between the ELC test, Initial Lifts and Final Lifts for three joints (Lumbopelvic, Hip, Knee), where * indicates $p < 0.05$. Standard error bars are used to represent variance within the figure.*

Specifically, at the hip joint there was a higher DP measure during the ELC test compared to both the initial ($p < 0.001$) and final ($p = 0.001$) lifts in the work session, but no difference between the initial and final lifts ($p = 1.00$). Similarly, DP was higher at the knee joint during the ELC test compared to the initial ($p = 0.037$) and final ($p = 0.029$) lifts in the work session, but there was no difference between the initial and final lifts ($p = 1.00$).

4.4.2 Interaction Effects

Task had an independent effect on the hip DP measures, but interaction effects were found for the lumbopelvic and knee joints. While task does not have an independent effect on DP at the lumbopelvic joint, there was an interaction effect when task interacted with lifting height ($F(4,76) = 8.2$, $p < 0.001$, $\eta^2 = 0.301$). For the knee joint, there was also a height*task interaction effect (F(4,76) = 4.74, $p = 0.002$, $\eta^2 = 0.2$), suggesting the task effects at the knee were dependent on the height conditions.

The height*task interaction effects are shown in *Figure 14.* At the lumbopelvic joint, the DP values were higher for the ELC test compared to the initial lifts ($p = 0.04$) at the floor-knuckle height, and the ELC test DP values were lower than both the initial lifts ($p < 0.001$) and final lifts ($p = 0.005$) at the knuckle to shoulder height. At the knee joint, the ELC test DP values were higher for the ELC test compared to both the initial lifts ($p = 0.004$) and final lifts ($p = 0.001$) at the floor-shoulder height.

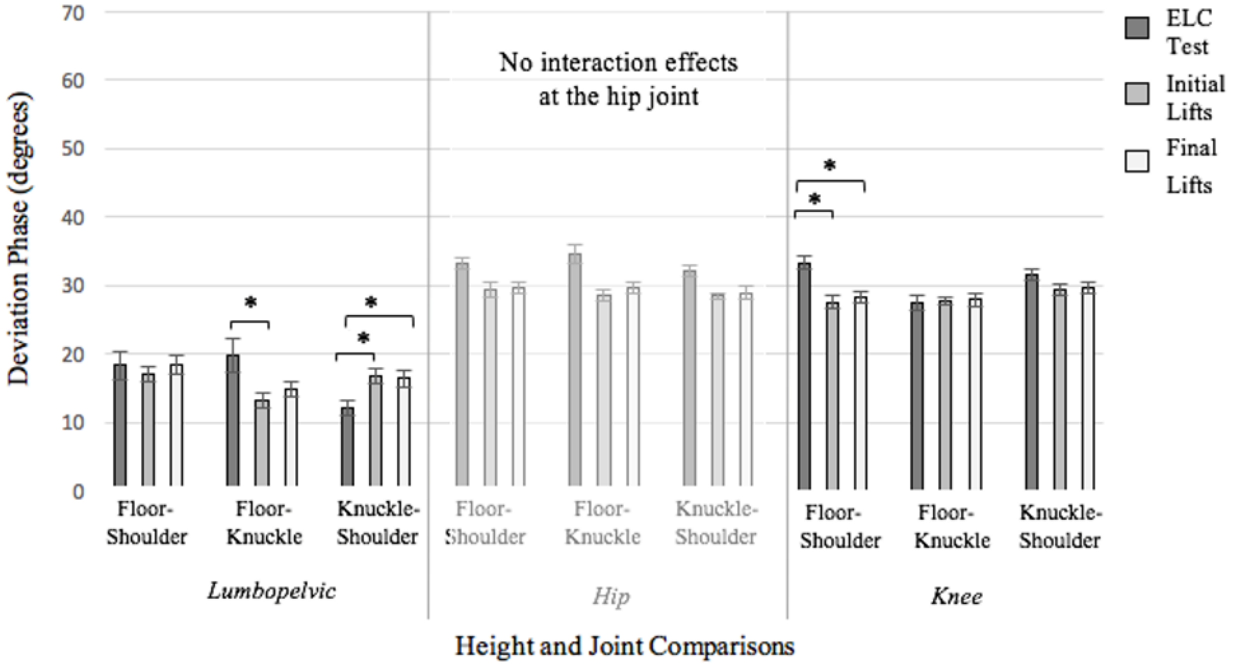

*Figure 14 DP height*load interaction effects at each joint (lumbopelvic, hip, and knee) for each task type (ELC, Initial Lifts, Final Lifts) and lifting height (Floor-Shoulder, Floor-Knuckle, Knuckle-Shoulder), where * indicates $p < 0.05$. Standard error bars are used to represent variance within the figure.*

4.3 Qualitative Measures

Additionally, subjective measures of perceived fatigue, boredom, and exertion during the work simulation were recorded at the end of the 90-minutes of lifting. The full questionnaire can be found in *Appendix B-3.* Responses were given on a scale from 0-10, where a score of '10' indicated that participants were at maximum exertion, fatigue or boredom, and a score of '0' indicated no exertion, fatigue, or boredom. The results from those questionnaires is summarized in *Table 6*.

Table 6 Perceived Exertion, Fatigue, and Boredom during the 90-minute work simulation

Factor	Mean (±) Standard Deviation
Exertion	6.8 ± 1.5
Fatigue	5.7 ± 2.3
Boredom	6.4 ± 2.1

5.0 Discussion

5.1 Key Findings

Overall, there are differences in coordination measures between the ELC screening test, the initial lifts in the work simulation, and the final lifts in the simulation; however, the differences were not consistent across joint, height, and in some cases load conditions. Results from this study show that the coordination pattern at the lumbopelvic joint was the most in-phase and stable of the three joints, with comparatively lower MARP and DP values across tasks and heights. Additionally, the lumbopelvic joint stood out as the only joint where there was a difference in coordination pattern between initial and final lifts from the work simulation, and where there was no difference between the ELC test and either part of the work simulation. When considering lumbopelvic coordination, hypotheses 1 and 2 were supported, as there was no difference between the ELC test and initial lifts, and a difference present between initial and final lifts; however, hypothesis 3 was not supported when considering movement about the lumbopelvic joint, as there was no difference between the ELC test and final lifts.

Comparatively, at the hip joint there was a difference in coordination pattern and variability between the ELC test and both initial and final lifts, independent of changes in load or height. Similar to the changes found at the hip joint, at the knee there were differences between the ELC test and work lifts in both coordination pattern and variability; however, these differences at the knee were sensitive to changes in height and load conditions. The knee MARP ELC test values were higher compared to the initial and final lifts with the 4.54 kg load condition, and within the floor-knuckle lifting range, but were lower or more in-phase at the floor-shoulder range compared to the final lifts. The ELC test had more variability at the knee compared to the initial and final lifts at the floor-shoulder condition. Results at both the hip and knee supported hypothesis 3, as there was a difference between the ELC test and final lifts, but there was also a difference between the ELC test and initial lifts (not supporting hypothesis 1) and no difference between initial and final lifts (not supporting hypothesis 2). Therefore, it appears coordination changes with task type are dependent on the joint of interest.

Although the results indicate there is a change in coordination with a change in task type, the differences were not as originally expected. It was thought that the ELC test and initial lifts would have the most coordinative pattern (lowest MARP) and be the most stable (lowest DP), as the lifts required little cognitive load, and the participants were "fresh" or not mentally and physically fatigued. Conversely, the final lifts were expected to result in the most uncoordinated pattern (highest MARP and DP), due to factors like boredom, fatigue, and learning. As a result, a reverse "L" shaped pattern was expected (low MARP and DP in the ELC test and initial lifting, higher values in the final lifting segments) when considering coordination measures (MARP and DP) between the ELC test, initial and final lifts. However, the ELC test proved to be the least coordinative (highest MARP) with the highest variability (highest DP) at the hip and knee, with the initial and final lifts exhibiting similar coordination patterns. Additionally, all three joints were expected to change coordination patterns similarly with a change in task type; however, the lumbopelvic joint commonly exhibited a "U" shape at the two largest lifting ranges (floor-shoulder, and floor-knuckle), with the final lifts being the most variable and less in-phase and the early lifts being the most stable and in-phase. These unexpected differences prompt deeper consideration about the differences in constraints (obvious or not) between these tasks that may have influenced coordination.

Drawing on principles from DST, these changes in coordination may be best explained from the perspective of Newell's model of interaction constraints (Newell, 1986), recently adapted by Glazier (2017). In this model, constraints from three overarching groups interact to dictate the movement strategy best suited for a task, as depicted in *Figure 15* (Glazier, 2017; Holt, Wagenaar, & Saltzman, 2010; Newell, 1986). The first group of constraints are related to the environment, which includes both the physical environment (equipment layout, lighting, temperature, etc.) and the tools and equipment found in that environment (shelving heights, loads, etc.) (Glazier, 2017, Newell & Jordan, 2007). The next group of task constraints relate to the goals and objectives of task, and includes implied rules or expectations for a task (Glazier, 2017; McGinnis & Newell, 1982). Lastly, the third group, organismic constraints, considers both structural constraints like body weight and height, which are relatively fixed to an individual over time, and functional constraints like fatigue or boredom, which include both psychological and physiological factors that can change over shorter periods of time (Glazier, 2017, Newell & Valvano, 2017).

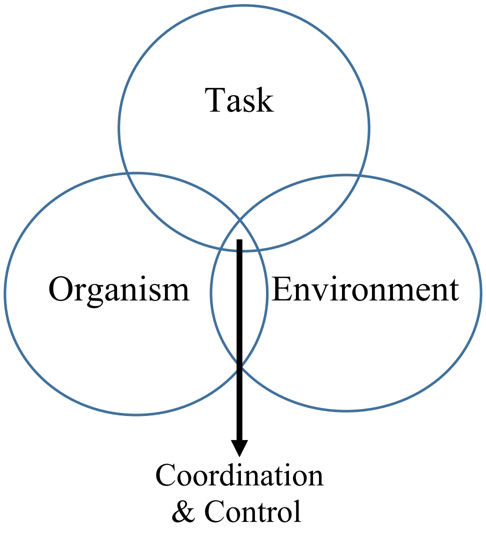

Figure 15 Newell's (1986) Constraint Model, as adapted by Glazier (2017) and Holt (2010) (Glazier, 2017; Holt et al., 2010; Newell, 1986)

As emphasized by Newell, van Emmerik, and McDonald (1989), all three constraint types work together to alter movement behaviour; however, differences in the relative contributions of each constraint type may be specific to the task at hand (Glazier, 2017). While all three of the task conditions explored in this thesis had the same structural organismic constraints (comparisons were made within-participants) and environmental constraints (the shelving heights and box loads were set), there were differences in functional organismic and task constraints between task types, as described in *Table 7*. Therefore, the increase in variability and coordination pattern seen in the ELC test compared to the initial and final work lifts at the hip and knee joints may be due to changes in task constraints, as the ELC test had a different task goal or objective. Additionally, individuals in the ELC test were observed directly and tested in a small area on one apparatus, potentially influencing the participants' interpretation of the task objective, imposing further task constraints. More structure and increased constraint may be more restrictive, altering coordination pattern. Individuals may be most coordinative and stable without any constraints, free to move naturally. Adding constraints, such as adding novel rules, forcing pace, or introducing more perturbations may alter the coordination pattern, creating more variability in the movement. In contrast, the increased MARP or less in-phase coordination seen in the final lifts at the lumbopelvic joint may be a result of increased functional organismic constraints in the final lifts, including fatigue, boredom, or motivation. The initial lifts appear to represent the task condition with the least amount of constraints, with more freedom to move, less pressure to perform due to less observation compared to the ELC test (less task constraints), and less fatigue or boredom compared to the final lifts after 90 minutes (less functional organismic constraints). This freedom or lack of constraint may allow lifters with the flexibility required to find a more coordinated or natural movement, contributing to the relatively lower DP and MARP values in the initial lifts conditions.

Table 7 Functional organismic and task constraints for the ELC test, initial lifts, and final lifts

Constraint Type	ELC Test	Initial Lifts	Final Lifts
Functional Organismic	- *Boredom*: Limited boredom at the beginning of study - *Fatigue*: No fatigue at the beginning of the study	- *Boredom*: Limited boredom after starting a new task - *Fatigue*: Limited fatigue after breaks throughout the ELC test, and a 15 minute break before initial lifts	- *Boredom*: Reported boredom as 6.4± 2.1 /10 after 90 minutes of consecutive lifting - *Fatigue*: Reported fatigue as 5.7 ± 2.3 /10 and exertion as 6.8 ± 1.5 /10 after 90 minutes of consecutive lifting
Task	- *Goal:* To lift the highest load possible, within 1-minute - *Implied constraints:* Individuals were watched, asked about their perception of the task (RPL scores), and confined to a relatively small area	- *Goal:* Lift as many boxes as possible for remuneration, while comfortable and at their own pace - *Implied constraints:* Individuals were not watched (directly), allowed to move freely and approach the box how they wish	- *Goal:* Lift as many boxes as possible for remuneration, while comfortable and at their own pace - *Implied constraints:* Individuals were not watched (directly), allowed to move freely and approach the box how they wish

Although Glazier's interpretation directly relates to movement in sport, this theoretical framework has more general implications on movement behaviour and the role of constraints. Movement involves combining available degrees of freedom to form coordination patterns that suit specific purposes and situations (Glazier, 2017). The differences between the early trials to both the later trials and the ELC test may be due to changes in constraints, as "in principle, small-scale changes in one of the three categories of constraints can have a large-scale impact on the ensuing coordination" (Newel, 1989). As depicted in *Figure 16,* and as is evident by the results, small differences in constraints results in significant differences in both the overall coordination pattern chosen for each task type, but also the amount of variability within that pattern.

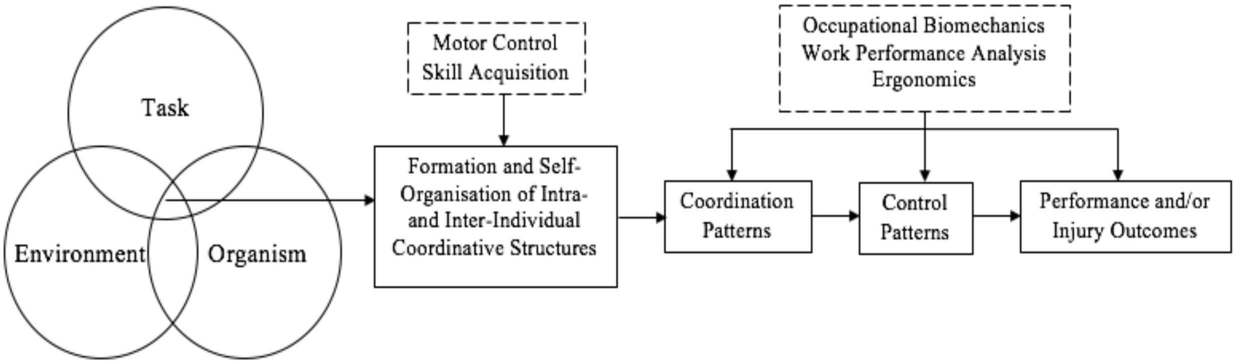

Figure 16 A general overview of the role of constraints in influencing movement behaviour and outcomes, for consideration in Occupational Biomechanics adapted from Glazier's Grand Unified Theory (GUT) for sports performance (Glazier, 2017)

5.2 Implications of Coordinative Changes

These changes in coordination pattern and variability may be important in the context of pre-employment screen design. As the three joints were influenced differently by changes in task and organismic (functional) constraints, and as the influence of those constraints on changing coordination were modulated by differences in environmental constraints (lifting range and load), constraints should be an important consideration in the future design of screening tests. If administrators or researchers want to mimic or replicate a job, or if they are interested in the movement strategy used during the task, tests should not only match the job's environment (layout, shelf heights, etc.), but should also consider the influence of other constraint types including (functional) organismic and task constraints. If one fails to account for factors within all three constraint groupings, the resulting movement strategy used within a screen may not replicate the strategy demonstrated in the workplace. Moreover, through the use of tools associated with DST, it may be possible to develop screens that better mimic workplace movement behaviour by first ensuring that coordination patterns are consistent between the work and screen.

Additionally, the overall stability and in-phase coordination pattern present in the lumbopelvic joint across height, load and task conditions may be important to consider in a pre-employment screening or return to work capacity. If the lower back or lumbopelvic joint is the joint of interest in a return to work screen or pre-employment screen, the ELC test may challenge candidates to control lifting actions using a movement behavior (coordination) similar to that which they would adopt in the workplace. However, this study does not add information to delineate a relationship between coordination and risk. Future work should continue to explore relationships between coordination and risk, such that measures of coordination could be used during pre-employment screens to assess one's ability to safely lift at work.

5.3 In the Context of Previous Literature

Previous studies have supported this link between changes in coordination and alterations in constraints, particularly with functional organismic constraints. The changes in lumbopelvic coordination over the 90 minutes of lifting cannot be attributed to changes in environmental or task constraints, as the same apparatus was used and the initial and final lifts had the same objective attached. However, there were changes in functional organismic constraints over time. Functional organismic constraints include physiological and psychological factors that can change within an individual over a relatively short period of time, and include but are not limited to heart rate, emotions, attention, sensory perception, and motivation (Glazier, 2017). It has been suggested that in an athletic setting, functional organismic constraints, specifically intentions or motivation, have a strong influence on coordination (Kelso, 1995), perhaps due to their ability to fluctuate within a task or over time. Therefore, other functional organismic constraints such as fatigue, boredom or lack of motivation, and effort may be affecting movement behavior in a similar way between the initial and final lifts.

It could be reasonable for both physiological and psychological functional constraint differences that occurred during the 90-minute work trial to affect coordination. Fatigue is one factor that may account for some of the change in movement strategy about the lumbopelvic joint, as fatigue has previously been shown to produce altered coordination (Cowley & Gates, 2017; Sparto et al., 1997). Similarly, boredom may affect work behavior, especially in long duration tasks without variability as it lacks intellectual stimulation (Fishel & Kimbler, 2005; Fisher, 1993)**.** There was a minor cognitive element incorporated into the work task, as participants read a lifting order, memorized the order, and then executed lifts and lowers in the prescribed order; however, this may not have been stimulating enough to ward off boredom, or the duration of the task may have reduced the interest in the task over time. Cognitive load has previously shown to alter coordination pattern and variability in walking, with higher MARP values being observed at the hip with preferred speeds and low cognitive load (Ghanavati et al., 2014), suggesting differences in cognitive load may have contributed to changes in coordination between tasks. Due to the lack of performance feedback, task complexity, task variety, and autonomy, participants in this work environment might be more susceptible to boredom (Fishel & Kimbler, 2005; Fisher, 1993), applying an organismic constraint on the task, potentially influencing coordination.

Although these functional organismic constraints were not objectively measured, fatigue, effort level and boredom were subjectively recorded at the end of the 90-minute work simulation. The post-collection questionnaire determined that participants did perceive exertion (6.8 ± 1.5 / 10), boredom (5.7 ± 2.3 / 10), and fatigue (6.4 ± 2.1 / 10) during the work simulation; however, the wide range of responses suggest these perceptions are quite variable across individuals. Exertion responses ranged from 4-9/10, while boredom ranged 2-10/10 and fatigue ranged 0-9/10. The variability in these subjective measures is understandable, as functional organismic constraints are individual-dependent and perceived by the individuals. Therefore, certain individuals may be more susceptible to psychological factors, including boredom or disinterest (Fischel & Kimbler, 2005; Smith, 1955), which is an important consideration when designing work and pre-employment screens to match specific constraints.

The overall in-phase and stable coordination pattern seen in the lumbopelvic joint, and the sensitivity of this joint to functional organismic constraints may be due to the role of the lumbopelvic joint in core stability and protecting against injury. Core stability, defined as the ability to control the trunk over the pelvis and thigh to promote optimal production and transfer of force and motion through the lower extremities (Kibler, Press, & Sciascia, 2006), is essential for daily living tasks and for the prevention of musculoskeletal disorders (Ebenbichler, Oddsson, Kollmitzer, & Erim, 2001). This core stability may allow changes to occur upstream at the trunk to optimize and stabilize conditions downstream at the lower limbs and to maximize function (Kibler et al., 2006). Additionally, in studies investigating lumbopelvic coordination in walking, phase angles were shown to change with age at the lower back (McGibbon & Krebs, 2001), suggesting this stability or control may diminish with age. Furthermore, McGibbon and Krebs (2001) have found pelvis and trunk movement alters in response to lower-limb weakness or disability in older adults to preserve trunk stability. This stability in the lumbopelvic joint earlier in life and the apparent changes with age may have implications in return to work and pre-employment screening, as the lumbopelvic joint's altered coordination pattern with fatigue or boredom may be further amplified with age.

Previous literature has also given reasoning for changes in task constraints leading to changes in movement behavior and coordination. For this study, the primary difference between the ELC test and work trials is implicit or explicit task objectives. As $30 was the maximum remuneration available for the work trial, the participants had an explicit monetary goal. In contrast, the participants were told to reach the maximum load they could on the ELC test. This change in task goal from a "do-best" goal (ELC test) to a monetary and specific goal (work trials) has been shown to alter performance on a task, especially with time (Locke & Bryan, 1967). Again, this may justify adjusting screens to match all constraints, including task goals, in order to better replicate the workplace.

The overall higher MARP in the ELC test may be due to more constraints in the ELC test compared to the initial and final lifts. The participants remained in front of the shelving unit for all ELC test lifts and had set handles, while the participants approached the shelves in different ways and used different handling strategies in the work simulation. This structure or lack of freedom to move in the ELC test was further enhanced with a time constraint, as all ELC test lifts in a cycle must be completed within a minute. These changes are consistent with research by Chiu & Chou (2012), which found differences in hip-knee coordination between preferred and forced slower or faster paces, and by Ghanavati et al. (2014), which found a greater hip MARP when walking at a slower forced pace than at a preferred pace. This is consistent with the change in hip MARP between the ELC test and initial/final lifts, with the forced pace ELC showing a higher MARP value. Therefore, coordination appears to be affected by implied task constraints when presented with a time limit for a task, so duty cycles and time constraints should be taken into consideration when designing or applying the use of screens. Additionally, during the ELC test participants answered questions during the test where their answers were recorded, knew they were being tested, and were directly observed, which can contribute to changes in behavior, as described by the Hawthorne Effect (McCambridge, Witton, & Elbourne, 2014). Differences in movement strategy may be attributed to implied constraints of the task, increasing the participants' "pressure" to perform well, altering the task objective and applying constraints to movement. This may be important in other screening tests, as being tested to enter or return to the workforce may add additional constraints, altering the movement of the worker and perhaps the results.

5.4 Alternative Explanations

One explanation for the changes in coordination pattern between the three task conditions is practice or experience. As experience has been shown to affect lifting strategy (Plamondon, et al., 2014), those with MMH experience were excluded from the study to limit experience as a confounder; however, this may result in learning effects during the study. The order of the tasks were not randomized, with the ELC test always preceeding the intitial and final lifts; therefore, the participants were introduced to structured lifting during the ELC test, and had then practiced their lifting technique by the initial lifts and had 90 minutes of practice by the final lifts. Previous research has shown that movement strategies can change with more familiarity or training with a task (Gallahue & Ozmun, 1995). It is possible that the higher MARP and DP values seen in the ELC test at the knee and hip may reflect the novelety of the ELC test, and the participants adopted a more natural or in-phase coordination pattern during the initial and final lifts as they practiced over time. Although this could be considered a functional organismic constraint, it steadily changed across all three tasks, and there was no subjective or objective data to determine if learning did occur.

Similarly, although differences in coordination in the ELC test may be attributed to being observed and differences in task objective, task constraints were not directly measured in this study. Despite the loads lifted in the work trials being based on ELC test maximum loads, and the shelving heights being identical between tasks, it is possible differences in movement behavior is related to slight changes in environment, or differences in processing. During the ELC test, the box handles extended laterally from the milk crates' built in handles, allowing the participants to keep a neutral wrist posture while lifting maximal loads. Handle orientation has been found to alter both physical and psychological changes during lifting, eliciting changes in wrist and forearm posture (Wang, Chung, & Chen, 2000) and perceived heaviness (Shih & Wang, 1997); therefore, this change in handle positioning may have influenced posture or movement behaviour, or induced further constraints on movement in the ELC test. Furthermore, heavier loads were lifted in the ELC test up to the participants' RPL, so there may be some fatigue effects; however, every participant was given unlimited resting time in between lifts, with a minimum of 1 minute rest. Additionally, during the work tasks participants approached the lift from different angles by walking up to one of three shelves to perform the lift. In contrast, the ELC test required less movement when approaching the lift, as all lifts were performed on the same shelf structure, which had the three shelf heights built into one unit. Lastly, the lifting cycles were cut differently between the ELC test and work trials, with the maximum and minimum forearm position being used in the ELC test to identify lift start and end points for each trial, while the work trials were cut using the shelf sensors with 100 ms added before and after the cut-offs.

This study had substantial external validity, as the participants were allowed to move freely as they would in the workplace, with no specific instructions regarding posture, position or lifting strategy; however, this may have resulted in more variation in movement strategy between individuals or between trials for the same individual. As the sample size in this study was smaller than intended, this study may not have been sufficiently powered to detect differences in movement strategy, and some of the differences may be due to outliers in movement strategy. Additionally, constraint differences were not isolated, meaning one constraint (ex: fatigue) may be driving the differences, or many constraints may be interacting to produce changes in behavior (ex: fatigue, motivation, and practice). More research is needed to identify the impact of specific constraints on movement and coordination, specifically in the context of lifting.

5.5 Limitations

There are some barriers when trying to analyze human movement in the workplace. Advanced measurements such as motion capture are difficult to set up in a work environment without obstructing the task or the measurement. In contrast, simulating job demands in a laboratory setting has its limitations. Most laboratory-based lifting studies are controlled, with the participants moving under the watch of an observer, and where data are collected for a short period of time in a small amount of space, with little movement. One aim of this study was to create a realistic workplace simulation. This was obtained by blinding the participants to the real objectives of the study, which was to analyze their movement during the lifting tasks. Also, a more realistic setting was created by considering a longer work simulation to mimic a repetitive lifting activity, varying the specific lifting actions in a pragmatic way, and not giving specific feedback or pacing constraints beyond those outlined above. However, for the study design to be more representative of the workplace and have more external validity, the internal validity was influenced, and as such there were specific limitations.

There were some limitations in the study design, collection and processing that need to be taken into account when considering the findings. If the ELC test is used outside of its original design to make determinations about movement strategy, clinicians or kinesiologists are using only a select few lifts to estimate the general strategy that would be used in the workplace; however, this is a limitation of the study, as only one ELC test trial was compared to the average of three work trials for the one repetition maximum condition. This may not allow for an accurate comparison, as there may be too much or too little variability within the three work trials, giving an inaccurate depiction of overall coordination. It may be that the strategy used in the ELC test was present in only one of the work trials, but after averaging across all three the work trials, a difference was detected. Similarly, the one lift seen in the ELC test may have been an outlier for that individual, and not represent the overall strategy used (Payton & Bartlett, 2007; Bates, Dufek, & Davis., 1992). The number of trials selected to compare may be too limiting to create an accurate determination on movement differences, with previous research showing the need for more than three trials to create a stable estimate (Dunk, Keown, Andrews, & Callaghan, 2005). Future studies should aim to compare more trials, over longer durations to create a more stable estimate of movement behaviour in both the ELC test and work simulation.

Additionally, the ELC test did not exactly match the work simulation, and the order in which the participants completed the task types (ELC test and work simulation) was not randomized. The ELC test equipment included box handles that differed compared to the work boxes and had a shelving unit with one centre post rather than four posts (one on each corner). Additionally, the ELC test boxes had a maximum capacity of 31.7 kg, which forced one participant to finish a subtest prematurely; however, that participant's RPL ranking was 7.5 (*Table 2*), which is 0.5 from the subtest cutoff, so influence may have been minimal. These inherent differences with the ELC test may not be a limitation of the study design exclusively, but may also be a limitation of occupational pre-employment screens themselves, as screening always precedes work, and work tasks will likely have varying handle grips, shelving structures, and load limits. Another limitation is that the effort put forth in the ELC test determined the amount of work required in the work trials. Psychophysical limits may greatly differ from physical limits. Participants that reached their true physical maximum during the ELC were then required to lift 75% of their maximum in the work trials. However, participants that ended the subtest before reaching their physical maximum or rating their perceived load higher may have been lifting at a load much lighter than their physical 75% maximum in the work trials, thereby varying the amount of effort required participant-to-participant. It is worth noting that participants had no real incentive to reach their maximum in the ELC test or to put in a full effort, which differs from a true ELC test where users are motivated by obtaining or returning to employment.

Additional limitations due to processing may have affected the comparisons between task types. In the ELC test, participants always remained fully facing the testing apparatus, as there was no need to approach from a different angle. In the work trials, participants could approach from any direction, as there were four stations in the simulation. Therefore, the sagittal angles may not have captured all of a segment's flexion/extension angles, as the participant may not have been parallel with the lifting apparatus. Also, the ELC test lift start and end points were defined by forearm position during the lift, while the work trials lift cycles were defined by the shelving sensors. Although each angle was checked manually to ensure sensor drop-out or visual 3D cut-offs were appropriately applied, there may still be differences in the timing of lifting cycles, leading to more or less data included in the relative phase curves.

Lastly, for the purpose of this study only the trunk, hip, thigh and shank were analyzed. Based on observations during collections, many participants began to throw or drop boxes, swing their arms, or switch to one-handed lifts as the work trials progressed, therefore future analysis may focus on whole body behaviors in the work place and how they relate to functional organismic constraint differences in pre-employment screening compared to work simulations. Additionally, there was a lack of objective measures for the functional organismic constraints. Quantifying fatigue, effort, and boredom would be valuable for determining if these factors influence coordination and behavior. It is also worth noting that a "half-cycle" was used as the input for the relative phase analysis. Typical use of relative phase analysis involves analyzing cyclical or oscillating movements, where the movement ends in the same position as the start; however, as only the lift portion was analyzed, rather than the lower-lift cycle, this may have some implications for interpretation and comparison to previous and future work on lifting coordination.

Other factors that may have resulted in coordination changes during these tests, such as age, MMH experience, and sex, were controlled for in the exclusion criteria. This study aimed to reduce physical fatigue through set rest breaks and sub-maximal relative loads in the work simulation. Although it cannot be objectively determined, the study design aimed to minimize fatigue by instructing and reminding participants to lift at a self-selected pace that could be sustained without muscular fatigue for an 8-hour shift; however, participants were paid per box lifted, which may have motivated workers to lift at a faster pace than in a set-pay position. Fatigue was also minimized through minimum rest breaks between ELC subtest, and between the ELC and work simulation, and through adjusting loads to a relative percent of each individual's maximum lifting capacity. However, future studies should aim to directly measure the effect of fatigue and other organismic constraints, and determine their effect on coordination.

5.6 Future Directions

If, as the results suggest, a small change in constraints is linked to changes in coordination pattern and variability, it may be important to tease out how constraints contribute to alterations in movement behaviour. Although this study compared three tasks with differences in constraints, future studies should attempt to isolate these constraints to determine their role in altering coordination. For example, isolating the effect of boredom on coordination, without the influence of fatigue and with no change in other constraint types, would help to identify the influence of this constraint on movement behavior. Additionally, objectively measuring these constraints, such as boredom, motivation, or fatigue, might help in identifying driving factors in coordination changes, as these factors were only subjectively inquired about at the end of the study.

Based on the differences found in this study between the ELC test and the work simulations, it is important for future work to continue to validate pre-employment and return to work screens if movement is of interest. To allow a participant or worker to move similarly to their movements in the workplace, screens should be as similar to the workplace as possible and consider factors associated with all three constraint types. This not only includes similar heights of shelves and loads, but could include giving similar incentives, rest times, and task objectives.

As this study tested how changing constraints could result in changes in coordination, investigating the first three steps of *Figure 16,* it is important to now identify how these changes influence performance outcomes or injury outcomes in the workplace. Although it is important to ensure a pre-employment screen replicates the work being tested for, how these changes in coordination affect a pre-employment screen's ability to identify at-risk movement or predict injury is unknown. Therefore, the impact of changing the first three steps of *Figure 16* on the last two steps (control patterns, and performance and/or injury outcomes) should be investigated in future studies.

6.0 Conclusion

The aim of this study was to identify differences in movement coordination between the ELC test, and early and late work trials. Differences between the ELC test and work tasks were evident based on both MARP and DP measures. Specifically, differences between the initial and final lifts occurred at the lumbopelvic joint, while differences in coordination measures between the ELC test and both the initial and final lifts occurred at the hip and knee joint. Differences in coordination pattern variability were found at the knee and hip between the ELC test and work tasks, but the lumbopelvic joint remained stable across all height and load conditions. Lastly, the participants appeared to have the most "in-phase" coordination at the lumbopelvic joint, and higher MARP and DP coordination values were found during the ELC test for the hip and knee. As the lumbopelvic joint appears relatively stable and in-phase, with no changes in coordination between the ELC test and work trials, the role of the lumbopelvic joint in overall coordination and stability, as it relates to injury and performance should be investigated. Based on task-related differences, it is possible that functional organismic or task constraints contributed to these changes, as structural environmental conditions (height, load, physical environment, etc.) were controlled for across task conditions. Factors such as fatigue, objective, boredom/interest, being observed, and motivation may influence an individual's behaviour, resulting in a change in movement strategy or coordination.

The relative contribution of all three constraints for Newell's model should be considered in future screen use and design (Glazier, 2017; Newell, 1986). Although the ELC test incorporates a psychological aspect in that participants decide on their maximum capacity, factors such as fatigue, motivation, and objective are not considered. It is important that the pre-employment screens not only match the physical demands of the job, but also ensure the pre-employment screen reflects task-specific, psychological and physiological demands of the work. When the participants were allowed to move freely in the initial work trials, with the least amount of constraint, the behaviour differed from both the ELC test and final work trials as the coordination pattern was generally more in-phase and stable. As small changes in these factors may have led to large changes in movement, pre-employment screens similar to the ELC test should be specific to the work in all aspects, to allow for potentially better agreement between the pre-employment screen and work. This includes similar environments, motivation, fatigue, workload, and attention. The aim of pre-employment screens is not only to better suit the worker to the job, but also to maintain the well-being of the worker; therefore, it is important both the physical and psychological capabilities are being matched for (Serra et al., 2007). The structure of the environment should not only be matched, but also the mental, social environment and organizational demands of the work (Fadyl et al., 2010), as these factors also influence functional capacity (Jones & Kumar, 2003). Although these factors were not objectively measured in this study, psychosocial, physiological and task changes appear to account for much of the differences between tasks types, as structural environment remained consistent. Future studies should attempt to quantify these factors and their role in movement behaviour, and the implication of coordinative changes on injury and performance.

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Appendix A: ELC Instructions (Epic Rehab, 2016)

The EPIC lift capacity test (ELC) determines the maximum lifting capacity of individuals during lifting and lowering tasks.

Typically, the ELC consists of 6 subtests, which gives the evaluator the option to conduct 1 of the first 2 subtests, the first 3 subtests in order, or all 6 subtests in order. Each subtest progresses in difficulty according to NIOSH guidelines, with increases in lifting ranges, loads, or repetitions.

The test includes three lifting ranges: knuckle to shoulder, floor to knuckle, and floor to shoulder. The shelf heights will be based on the participants' height, as described in *Table 1* below.

Table 5 Shelf Height Recommendations

Participant's Height (cm)	Lower Shelf Height – Knuckle (cm)	Upper Shelf Height – Shoulder (cm)
< 168	69	122
168-183	76	137
>183	84	145

There are two lifting frequencies: 1 repetition/cycle, and 4 repetitions/cycle. Each cycle will last a minimum of 30 seconds, after which the load should increase by 4.5 kg, up to their maximum acceptable weight (MAW). The starting weight for the first to subtests are set at 4.5 kg, and the starting load for subtests 3-6 are based off of relative percentages of the MAW produced in the first two subtests, rounded to the nearest 2.3 kg. A brief overview of the subtests can be found in *Table 2*.

Table 2 Subtest Overview

Subtest	Lifting Ranges	Repetitions	Starting Weight
1	Knuckle to Shoulder	1 rep/cycle	4.5 kg
2	Floor to Knuckle	1 rep/cycle	4.5 kg
3	Floor to Shoulder	1 rep/cycle	4.5 kg
4	Knuckle to Shoulder	4 reps/cycle	40% MAW from subtest 1
5	Floor to Knuckle	4 reps/cycle	40% MAW from subtest 2
6	Floor to Shoulder	4 reps/cycle	40% MAW from subtest 3

Note - MAW: maximum acceptable weight

After each cycle, the participant will be asked question 1, "*How much does this weigh?*", for which they will be provided in the rating chart in *Table 3*.

Table 3 Rating of Perceived Load (RPL) Chart

Rating	**Perceived Load**
1	Like Nothing at All
2	Very Light
3	Light
4	Light-Medium
5	Medium
6	Medium-Heavy
7	Heavy
8	Very Heavy
9	Extremely Heavy
10	Too Heavy

The participant's response will serve as the 'Rating of Perceived Load' (RPL). If at any point the participant rates the load ≥8 RPL, the subtest will be concluded and MAW recorded.

Additionally, the participant will be asked question 2 and 3, "*Do you think you could lift this load 8-10 times per day?*" and "*Can you lift heavier?". *If the participant answers with a RPL < 8, but answers no to either Questions 2 or 3, the subtest will conclude and MAW recorded.

If a full effort is obtained in the test, the participants' heart rate should increase with each subtest and load, the movement pattern adopted should change slightly with an increase in load, and the participants' perceived load should increase with each subtest.

Lastly, the participants' heart rate will be monitored periodically throughout the test. Also, the participant's behaviour will be monitored for high-risk work style (HRWS), which will be evaluated throughout the test as described in *Table 4*.

Table 4 High-Risk Workstyle Guidelines Chart

Interpretation: *1 – Continue with test* *2 – Evaluator corrects behaviour* *3 – Interrupt and correct; continue only if behaviour corrected*	**Horizontal Displacement**	**Stance**
	The distance between the load and centre of the spine at the sacrum during work tasks	*Maintain feet placement in a broad and stable stance during work tasks*
"1" Decreased probability of injury at this load	Within 7.5 cm at the end of the lift	Feet shoulder width or greater and staggered placement
"2" Slightly increased probability of injury at this load	Within 15 cm at the end of the lift	Feet less than shoulder width and staggered placement, or feet shoulder width or greater with parallel placement
"3" Injury likely at this load	More than 15 cm at the end of the lift	Feet less than shoulder width, with parallel placement

Each subtest will conclude if the participant:

- Has a RPL ≥ 8 (Question 1)
- Answers no to the Question 2 or 3
- Continues to display a HRWS ≥ 2, despite being corrected for this behaviour

After the subtest ends, the maximum weight the participant lifted for that test (MAW) will be recorded.

The EPIC test will conclude if the participant:

- Continues to exhibit HRWS of 3
- Displays unsafe lifting behaviour (throwing box, twisting, using lower body to help in lifting, etc.)
- Asks to stop

If the test ends due to unsafe lifting behaviour, the MAW recorded will be the load lifted before the unsafe behaviour commenced (the cycle before).

Appendix B-1: Demographics Questionnaire

For this study, we are determining appropriate guidelines for pacing, lifting heights, and load weights in a manual material handling (MMH) job. To determine these guidelines, which may vary due to a variety of factor, we request that you fill in the following questions:

Age: ____________years

Gender: ______________

Height: _____________cm

Weight: _____________ kg

Appendix B-2: Exclusion Criteria Questions

1) Have you previously worked a manual materials handling job (where your primary role was lifting or moving objects)?

2) What department are you enrolled in at the University of Waterloo?

3) Have you been injured in the last 12 months, requiring physical therapy or rehabilitation?

4) Are you involved in varsity athletics at the University of Waterloo, or in high-level (provincial or national) athletics?

Appendix B-3: Post-Collection Questionnaire

In order to determine work rate and pacing, please answer the following questions about your experiences in the two, one-hour lifting sessions. Each item is ranked on a Visual Analog Scale (VAS) from 0-10. Circle the number that you feel best represents your experiences with each factor listed. Please ask the student investigator for any questions regarding the provided scale or factor listed.

Perceived Exertion

0 1 2 3 4 5 6 7 8 9 10
No Exertion *Maximal Exertion*

Perceived Fatigue

0 1 2 3 4 5 6 7 8 9 10
No Fatigue *Maximal Fatigue*

Perceived Boredom

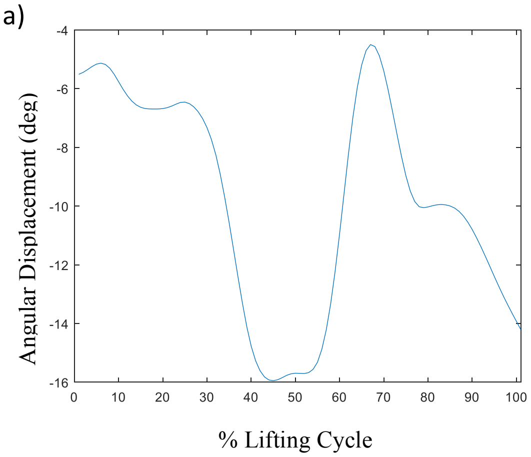
0 1 2 3 4 5 6 7 8 9 10
No Boredom *Maximal Boredom*

Appendix C: Visual Overview of Relative Phase Curve Analysis Process

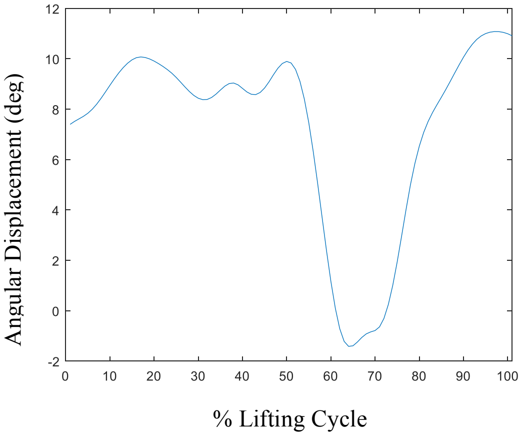
Thigh

Shank

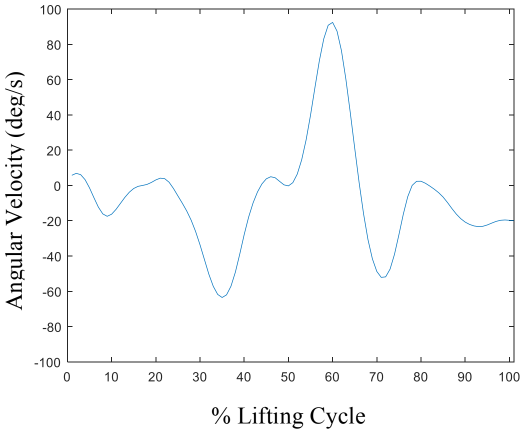
a)



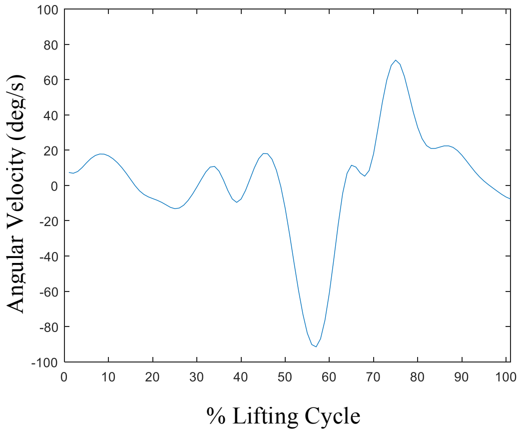
b)



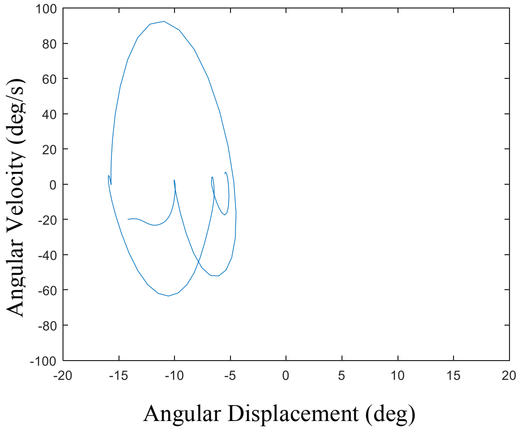
c)



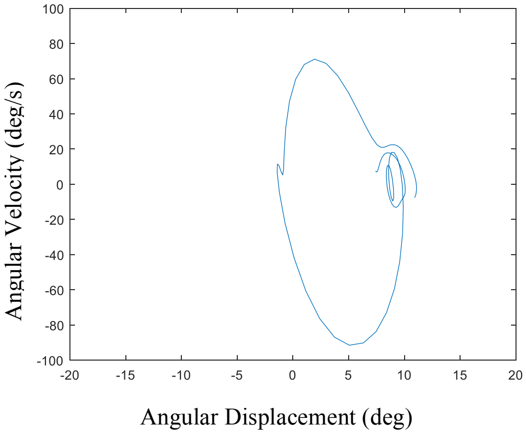
d)

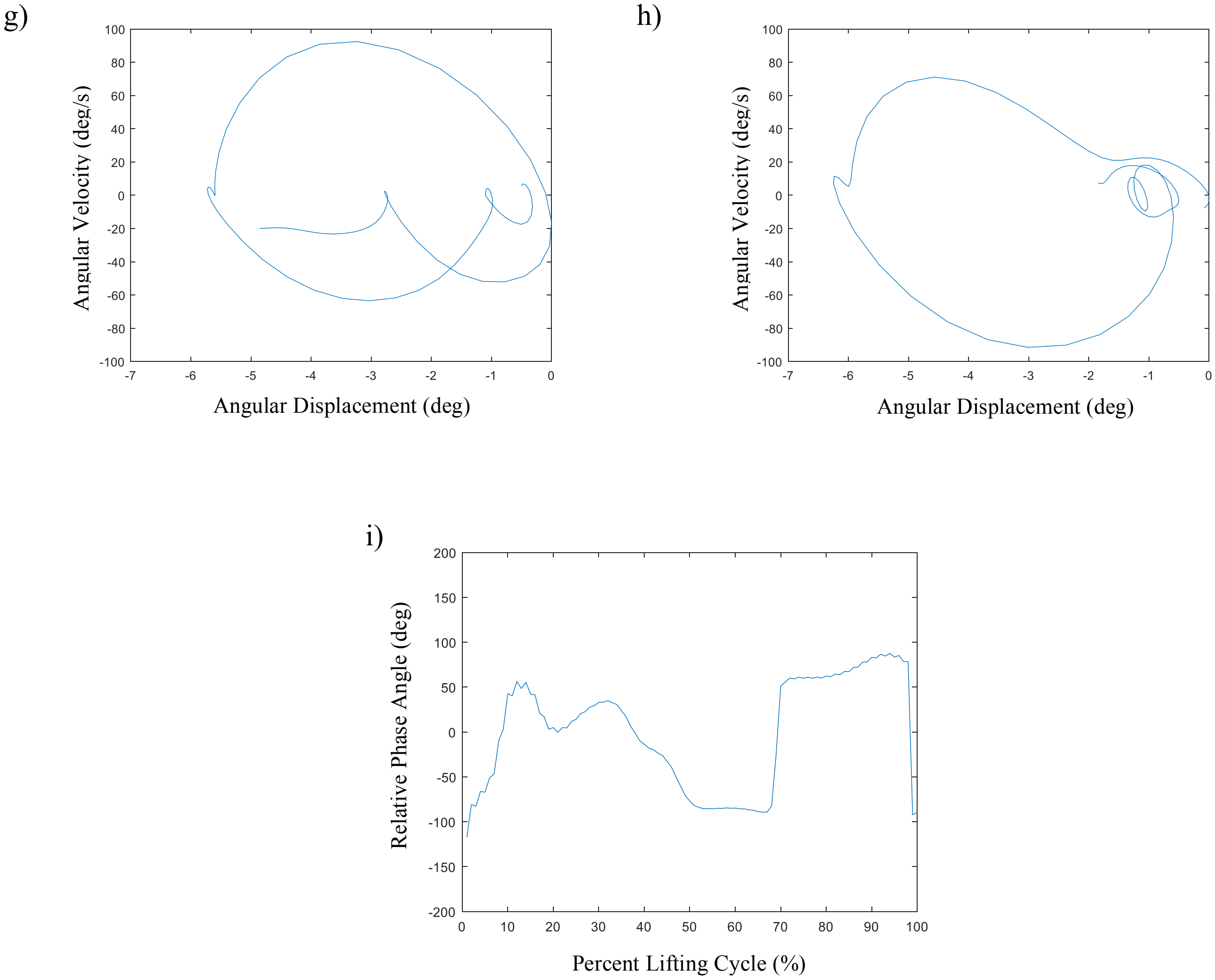


e)



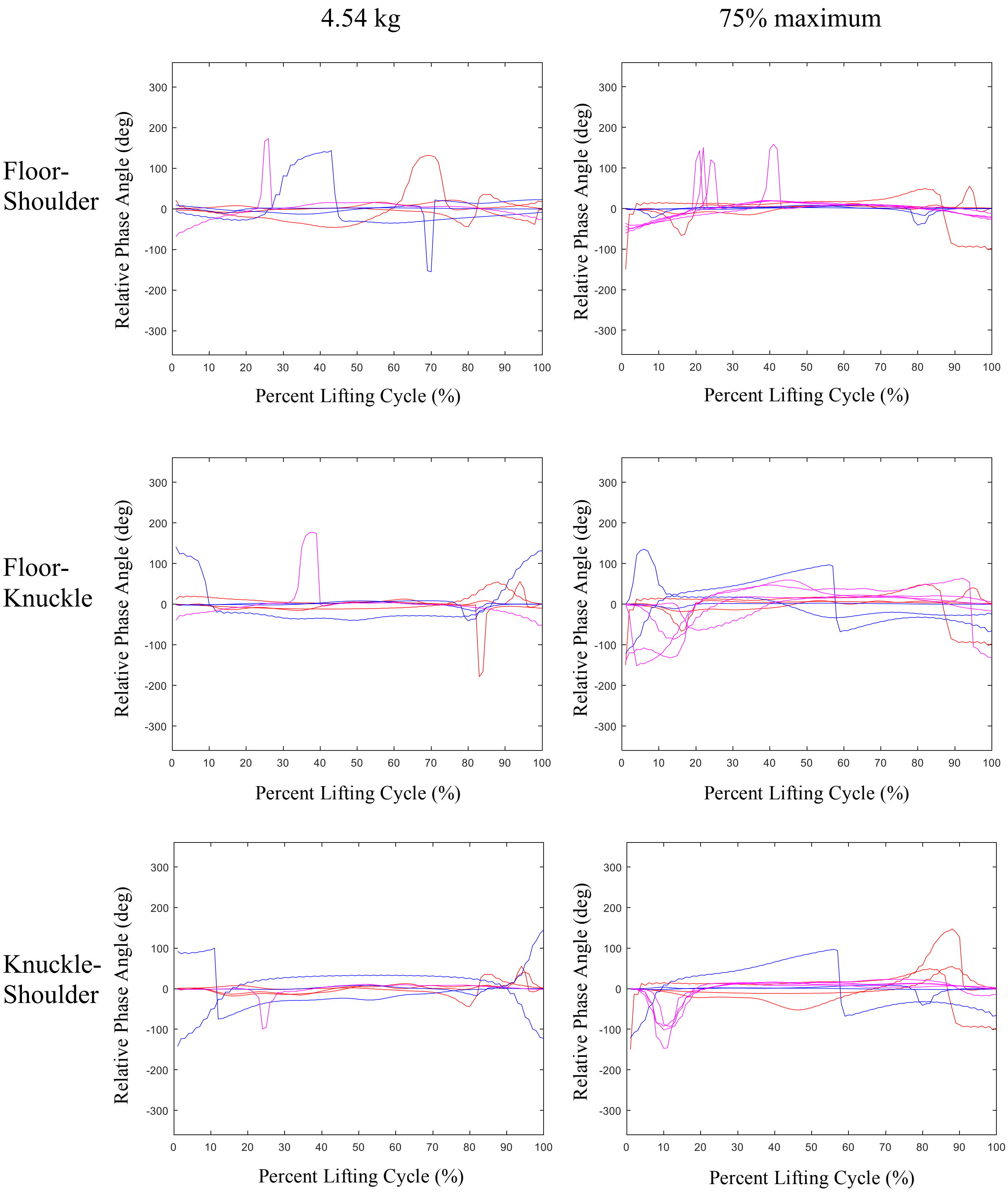
f)





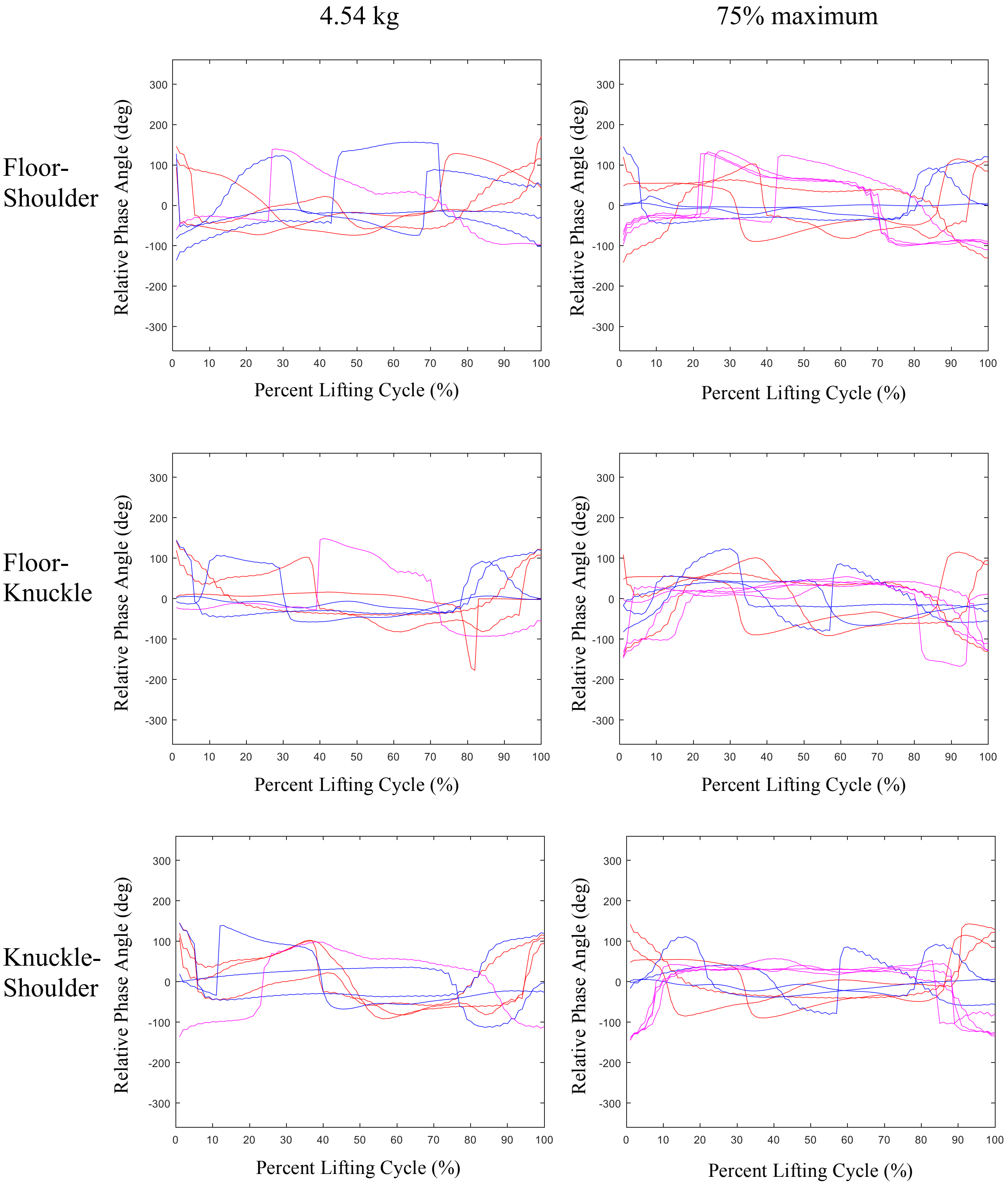
Appendix C – *For Participant 8, during an initial lift at floor to shoulder height with a 4.5 kg load. Rubberbanded (101 points) and filtered thigh (a) and shank (b) angular displacement were used to calculate thigh (c) and shank (d) angular velocity. The relationship between the angular displacement and velocity of the segments (phase portrait) is shown for the thigh (e) and shank (f). The phase portraits were centered for the thigh (g) and shank (f), and the Hilbert transform was used when normalizing the data to create the shank-thigh (knee) Relative Phase Angle (i).*

Appendix D-1: Relative Phase Curve Examples for the Lumbopelvic Joint



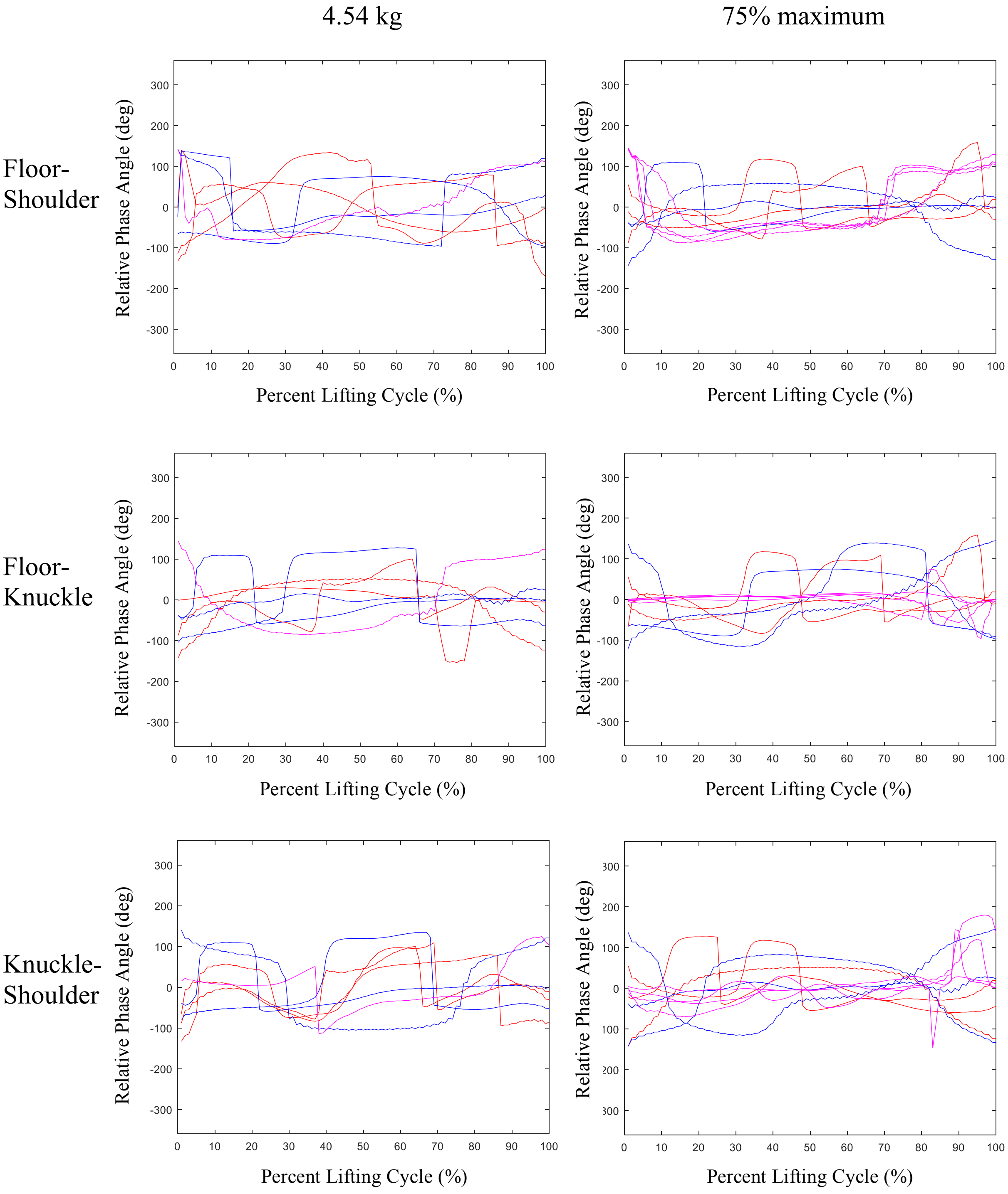
Appendix D-1 – *For Participant 8, the three initial lifts (red), final lifts (blue), and ELC test trials (magenta) are shown for the three height and two load conditions at the lumbopelvic joint*

Appendix D-2: Relative Phase Curve Examples for the Hip Joint



Appendix D-2 – *For Participant 8, the three initial lifts (red), final lifts (blue), and ELC test trials (magenta) are shown for the three height and two load conditions at the hip joint*

Appendix D-3: Relative Phase Curve Examples for the Knee Joint



Appendix D-3 – *For Participant 8, the three initial lifts (red), final lifts (blue), and ELC test trials (magenta) are shown for the three height and two load conditions at the knee joint*

Appendix E-1: Mean Absolute Relative Phase Univariate Tests

Effect	Joint	Sphericity	df, df_{error}	F	Sig.	Partial Eta Squared	Observed Power^{a}
Height	Lower Back	Sphericity Assumed	2, 38	2.180	.127	.103	.418
	Hip	Sphericity Assumed	2, 38	22.665	.000	.544	1.000
	Knee	Sphericity Assumed	2, 38	21.496	.000	.531	1.000
Load	Lower Back	Sphericity Assumed	1, 19	5.323	.032	.219	.591
	Hip	Sphericity Assumed	1, 19	.002	.965	.000	.050
	Knee	Sphericity Assumed	1, 19	.573	.458	.029	.111
Task	Lower Back	Sphericity Assumed	2, 38	4.151	.023	.179	.698
	Hip	Sphericity Assumed	2, 38	19.106	.000	.501	1.000
	Knee	Greenhouse-Geisser	1.5, 28.47	5.414	.016	.222	.725
Height * Load	Lower Back	Greenhouse-Geisser	1.285, 25.41	.656	.463	.033	.130
	Hip	Sphericity Assumed	2, 38	.307	.737	.016	.095
	Knee	Greenhouse-Geisser	1.528, 29.04	1.434	.252	.070	.251
Height * Task	Lower Back	Greenhouse-Geisser	2.565, 48.73	3.541	.027	.157	.705
	Hip	Sphericity Assumed	4, 76	2.709	.036	.125	.725
	Knee	Sphericity Assumed	4, 76	9.576	.000	.335	.999
Load * Task	Lower Back	Greenhouse-Geisser	1.438, 27.33	.420	.595	.022	.103
	Hip	Sphericity Assumed	2, 38	.579	.565	.030	.139
	Knee	Sphericity Assumed	2, 38	4.258	.021	.183	.710
Height * Load * Task	Lower Back	Greenhouse-Geisser	2.863, 54.4	1.014	.391	.051	.255
	Hip	Sphericity Assumed	4, 76	1.139	.345	.057	.342
	Knee	Sphericity Assumed	4, 76	.476	.753	.024	.157

Appendix E-2: Deviation Phase Univariate Tests

Effect	Joint	Sphericity	df, df_{error}	F	Sig.	Partial Eta Squared	Observed Power[a]
Height	Lower Back	Sphericity Assumed	2, 38	3.149	.054	.142	.570
	Hip	Sphericity Assumed	2, 38	1.274	.291	.063	.260
	Knee	Sphericity Assumed	2, 38	7.312	.002	.278	.918
Load	Lower Back	Sphericity Assumed	1, 19	.884	.359	.044	.145
	Hip	Sphericity Assumed	1, 19	.371	.550	.019	.089
	Knee	Sphericity Assumed	1, 19	.265	.613	.014	.078
Task	Lower Back	Sphericity Assumed	2, 38	.447	.643	.023	.117
	Hip	Sphericity Assumed	2, 38	18.753	.000	.497	1.000
	Knee	Sphericity Assumed	2, 38	6.234	.005	.247	.869
Height * Load	Lower Back	Sphericity Assumed	2, 38	.475	.626	.024	.122
	Hip	Sphericity Assumed	2, 38	.169	.845	.009	.074
	Knee	Sphericity Assumed	2, 38	1.338	.275	.066	.271
Height * Task	Lower Back	Sphericity Assumed	4, 76	8.197	.000	.301	.998
	Hip	Sphericity Assumed	4, 76	.675	.612	.034	.210
	Knee	Sphericity Assumed	4, 76	4.742	.002	.200	.941
Load * Task	Lower Back	Sphericity Assumed	2, 38	.353	.705	.018	.102
	Hip	Greenhouse-Geisser	1.404, 26.67	2.159	.147	.102	.341
	Knee	Sphericity Assumed	2, 38	.064	.938	.003	.059
Height * Load * Task	Lower Back	Sphericity Assumed	4, 76	.667	.617	.034	.208
	Hip	Sphericity Assumed	4, 76	1.261	.293	.062	.377
	Knee	Sphericity Assumed	4, 76	.627	.645	.032	.197

Appendix F: Pairwise Comparisons for Height, Load, and Task

MARP Pairwise Comparisons for Task Type

Joint	Task 2	Task 1	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
						Lower Bound	Upper Bound
Lower Back	ELC	Early Work	1.172	1.278	1.000	-2.184	4.528
		Late Work	-2.428	1.378	.283	-6.045	1.189
	Early Work	ELC	-1.172	1.278	1.000	-4.528	2.184
		Late Work	-3.600*	1.157	.017	-6.638	-.561
	Late Work	ELC	2.428	1.378	.283	-1.189	6.045
		Early Work	3.600*	1.157	.017	.561	6.638
Hip	ELC	Early Work	9.031*	1.768	.000	4.390	13.673
		Late Work	10.687*	2.266	.000	4.737	16.636
	Early Work	ELC	-9.031*	1.768	.000	-13.673	-4.390
		Late Work	1.655	1.458	.811	-2.173	5.484
	Late Work	ELC	-10.687*	2.266	.000	-16.636	-4.737
		Early Work	-1.655	1.458	.811	-5.484	2.173
Knee	ELC	Early Work	6.187*	1.682	.005	1.772	10.602
		Late Work	4.992*	1.681	.024	.578	9.406
	Early Work	ELC	-6.187*	1.682	.005	-10.602	-1.772
		Late Work	-1.195	2.506	1.000	-7.774	5.383
	Late Work	ELC	-4.992*	1.681	.024	-9.406	-.578
		Early Work	1.195	2.506	1.000	-5.383	7.774

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

MARP Pairwise Comparisons for Height

Joint	Height	Height	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
						Lower Bound	Upper Bound
Lower Back	Floor-Shoulder	Floor-Knuckle	1.009	1.484	1.000	-2.888	4.905
		Knuckle-Shoulder	2.676*	.927	.028	.243	5.110
	Floor-Knuckle	Floor-Shoulder	-1.009	1.484	1.000	-4.905	2.888
		Knuckle-Shoulder	1.668	1.401	.746	-2.011	5.347
	Knuckle-Shoulder	Floor-Shoulder	-2.676*	.927	.028	-5.110	-.243
		Floor-Knuckle	-1.668	1.401	.746	-5.347	2.011
Hip	Floor-Shoulder	Floor-Knuckle	3.131	1.271	.071	-.206	6.469
		Knuckle-Shoulder	11.715*	2.040	.000	6.360	17.071
	Floor-Knuckle	Floor-Shoulder	-3.131	1.271	.071	-6.469	.206
		Knuckle-Shoulder	8.584*	1.990	.001	3.360	13.808
	Knuckle-Shoulder	Floor-Shoulder	-11.715*	2.040	.000	-17.071	-6.360
		Floor-Knuckle	-8.584*	1.990	.001	-13.808	-3.360
Knee	Floor-Shoulder	Floor-Knuckle	-2.409	2.220	.874	-8.238	3.419
		Knuckle-Shoulder	10.076*	1.888	.000	5.120	15.033
	Floor-Knuckle	Floor-Shoulder	2.409	2.220	.874	-3.419	8.238
		Knuckle-Shoulder	12.486*	1.937	.000	7.401	17.570
	Knuckle-Shoulder	Floor-Shoulder	-10.076*	1.888	.000	-15.033	-5.120
		Floor-Knuckle	-12.486*	1.937	.000	-17.570	-7.401

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

MARP Pairwise Comparisons for Load

Joint	Load 1	Load 2	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
						Lower Bound	Upper Bound
Lower Back	4.5 kg	75% max	1.974*	.855	.032	.183	3.764
	75% max	4.5 kg	-1.974*	.855	.032	-3.764	-.183
Hip	4.5 kg	75% max	-.060	1.333	.965	-2.850	2.731
	75% max	4.5 kg	.060	1.333	.965	-2.731	2.850
Knee	4.5 kg	75% max	1.052	1.390	.458	-1.857	3.960
	75% max	4.5 kg	-1.052	1.390	.458	-3.960	1.857

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

DP Pairwise Comparisons for Task Type

Joint	Task 1	Task 2	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
						Lower Bound	Upper Bound
Lower Back	ELC	Early Work	1.093	1.316	1.000	-2.361	4.547
		Late Work	.185	1.397	1.000	-3.483	3.852
	Early Work	ELC	-1.093	1.316	1.000	-4.547	2.361
		Late Work	-.909	.958	1.000	-3.423	1.606
	Late Work	ELC	-.185	1.397	1.000	-3.852	3.483
		Early Work	.909	.958	1.000	-1.606	3.423
Hip	ELC	Early Work	4.505*	.810	.000	2.380	6.631
		Late Work	3.853*	.851	.001	1.618	6.088
	Early Work	ELC	-4.505*	.810	.000	-6.631	-2.380
		Late Work	-.652	.719	1.000	-2.539	1.234
	Late Work	ELC	-3.853*	.851	.001	-6.088	-1.618
		Early Work	.652	.719	1.000	-1.234	2.539
Knee	ELC	Early Work	2.552*	.924	.037	.125	4.978
		Late Work	2.217*	.770	.029	.195	4.239
	Early Work	ELC	-2.552*	.924	.037	-4.978	-.125
		Late Work	-.335	.635	1.000	-2.002	1.333
	Late Work	ELC	-2.217*	.770	.029	-4.239	-.195
		Early Work	.335	.635	1.000	-1.333	2.002

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

DP Pairwise Comparisons for Height

Joint	Height 1	Height 2	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
						Lower Bound	Upper Bound
Lower Back	Floor-Shoulder	Floor-Knuckle	2.031	1.222	.339	-1.178	5.240
		Knuckle- Shoulder	2.826*	1.034	.040	.112	5.540
	Floor-Knuckle	Floor -Shoulder	-2.031	1.222	.339	-5.240	1.178
		Knuckle-Shoulder	.794	1.218	1.000	-2.403	3.992
	Knuckle-Shoulder	Floor-Shoulder	-2.826*	1.034	.040	-5.540	-.112
		Floor-Knuckle	-.794	1.218	1.000	-3.992	2.403
Hip	Floor-Shoulder	Floor-Knuckle	-.183	.667	1.000	-1.933	1.568
		Knuckle- Shoulder	.921	.710	.631	-.944	2.785
	Floor-Knuckle	Floor -Shoulder	.183	.667	1.000	-1.568	1.933
		Knuckle-Shoulder	1.103	.835	.607	-1.090	3.296
	Knuckle-Shoulder	Floor-Shoulder	-.921	.710	.631	-2.785	.944
		Floor-Knuckle	-1.103	.835	.607	-3.296	1.090
Knee	Floor-Shoulder	Floor-Knuckle	1.960*	.661	.024	.226	3.694
		Knuckle- Shoulder	-.468	.678	1.000	-2.249	1.312
	Floor-Knuckle	Floor -Shoulder	-1.960*	.661	.024	-3.694	-.226
		Knuckle-Shoulder	-2.429*	.682	.006	-4.220	-.637
	Knuckle-Shoulder	Floor-Shoulder	.468	.678	1.000	-1.312	2.249
		Floor-Knuckle	2.429*	.682	.006	.637	4.220

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

DP Pairwise Comparisons for Load

Joint	Load 1	Load 2	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	Upper Bound
Lower Back	4.5 kg	75% max	.727	.773	.359	-.891	2.345
	75% max	4.5 kg	-.727	.773	.359	-2.345	.891
Hip	4.5 kg	75% max	-.374	.615	.550	-1.662	.913
	75% max	4.5 kg	.374	.615	.550	-.913	1.662
Knee	4.5 kg	75% max	-.262	.509	.613	-1.326	.803
	75% max	4.5 kg	.262	.509	.613	-.803	1.326

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.