

# Exploring Biomechanical and Metabolic Determinants of Lifting Movement Strategy

By

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## **AUTHOR'S DECLARATION**

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

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

## Abstract

**Background:** Poorly designed manual materials handling (MMH) work, such as lifting, lowering, pushing, pulling, and carrying, can increase the risk of developing musculoskeletal disorders (MSD). To ensure MMH work is safely designed, digital human models (DHMs) can be deployed. A DHM enables a designer to simulate and understand the interactions between a worker and the work in a virtual environment, without the risk or expense of physical prototyping. However, our current understanding of how humans select movement strategies during MMH tasks limits our ability to accurately predict human postures in digitally simulated MMH environments. To address this limitation in our current understanding, more fundamental research is needed to uncover how biomechanics and energetics influence movement strategies during MMH work. Optimal Feedback Control (OFC) theory provides a comprehensive framework for explaining why individuals choose specific movement strategies. OFC proposes that people move in ways optimized for task-specific and situation-specific performance criteria, such as minimizing low back moments or metabolic cost. Currently, we lack a thorough understanding of the relevant performance criteria for MMH tasks like lifting, lowering, pushing, pulling, or carrying. By leveraging optimal feedback control theory as a framework to uncover biologically relevant performance criteria, in the future we can improve our ability to predict and simulate MMH movements.

**Purpose:** The study was designed to determine the effect task parameters including load mass and lift frequency and time (pre- and post-exploration) have on the biomechanical exposures and metabolic costs of lifting. A research paradigm designed to study optimal control of gait was adapted to investigate the biomechanical and metabolic determinants of lifting movement strategy.

**Methods:** Using a repeated-measures experimental design, participants performed four 7-minute bouts of repetitive lifting in two different sessions, a high load low frequency (HLLF) session and a low load high frequency (LLHF) session. Within sessions, participants completed lifting bouts under 4-different technique conditions, where the first and fourth bouts allowed participants to self-select their technique (SS<sub>1</sub>, SS<sub>2</sub>) and the 2<sup>nd</sup> and 3<sup>rd</sup> bouts required lifters to adopt squat (SQ) or stoop (ST) techniques, respectively. High and low loads were defined as 15% and 5% of maximum voluntary lifting capacity in a semi-squat posture. High and low

frequency were defined as 12 lifts per minute and 4 lifts per minute, respectively. Full body kinematics and VO<sub>2</sub> consumption were collected during all trials. Using a whole-body top-down rigid link modeling approach, the peak sagittal L4/L5 moment was calculated. Two-way repeated measures ANOVAs tested for significant differences in biomechanical exposure and metabolic cost between the SS<sub>1</sub> and SS<sub>2</sub> lifting bouts.

**Results:** The group mean peak sagittal L4/L5 moment was  $211 \pm 7$  Nm in the HLLF condition, and  $149 \pm 2$  Nm in the LLHF condition. This task condition main effect was significant ( $F = 91.89$ ;  $p < 0.001$ ) where the HLLF condition resulted in significantly greater peak sagittal L4/L5 moments ( $64.6 \pm 6.74$  Nm;  $p < 0.001$ ). However, no main effect of time ( $F = 1.22$  ;  $p = 0.28$ ) or interaction effect was found ( $F = 0.46$  ;  $p = 0.50$ ). Significant main effects of task ( $F = 30.06$ ;  $p < 0.001$ ), and time ( $F = 5.54$ ;  $p < 0.05$ ) were found for mean VO<sub>2</sub> consumption, but no interaction effect ( $F = 2.81$  ;  $p = 0.10$ ) was found. Post-hoc analysis revealed that the LLHF condition resulted in significantly greater VO<sub>2</sub> consumption ( $4.69 \pm 0.86$  mL.kg.min;  $p < 0.001$ ), and that the SS<sub>2</sub> technique had significantly greater VO<sub>2</sub> consumption ( $0.95 \pm 0.403$  mL.kg.min;  $p < 0.05$ ). An increase in VO<sub>2</sub> consumption in SS<sub>2</sub> was unexpected, so a secondary analysis was conducted to explore movement specific adaptations characterized using the Squat Stoop Index (SqStI). The SqStI analysis revealed that the mean for the last ten lifts across all lifting bouts was on average 13% greater in the LLHF condition relative to the HLLF condition (i.e. closer to a stoop lift). However, the change in SqStI between the SS<sub>1</sub> and SS<sub>2</sub> lifting techniques was 0.4 within the HLLF condition, and 1.3 within the LLHF condition.

**Discussion:** The magnitudes of the peak sagittal L4/L5 moments and relative VO<sub>2</sub> consumption experienced by the participants were primarily affected by task parameters such as load mass and lifting frequency, which was expected by design. The biomechanical exposure and metabolic cost of participants did not significantly decrease following exploration of different lifting movement strategies. This was contrary to the hypothesis, where it was expected that VO<sub>2</sub> consumption would decrease following exploration in the LLHF condition (i.e., learn to optimize for metabolic cost when the metabolic system is more challenged), and peak sagittal L4/L5 moments would decrease following exploration, but only in the HFLF condition (i.e., learn to optimize for biomechanical cost when the biomechanical system is more challenged). Instead, a significant increase in metabolic cost from SS<sub>1</sub> to SS<sub>2</sub> was observed across both task conditions. This could suggest a willingness to sustain a lifting movement strategy that increases metabolic

cost over time in order to avoid increasing the biomechanical exposure experienced. Ultimately, participants were either unwilling or unable to significantly adapt their lifting movement strategy within the constraints of each task in order to reduce metabolic cost. A secondary analysis of lifting postures revealed that the initial and final preferred lifting movement strategy may have been modulated by the task parameters, where participants overall preferred a more stoop-like lift in the LLHF condition compared to the HLLF condition. In addition, it was seen that participants did not reach similar end ranges within the squat and stoop lifting bouts. Assuming that an SqStI value of 0% is a full squat lift, and an SqStI value of 100% is a full stoop lift, then participants were 31.6% away from a full squat but only 17.1% from a full stoop. This highlights a potential limiting factor of functional capacity, where participants may require additional relative strength, ankle range of motion, or aerobic fitness to explore a similar range of lifting movement strategies within the squat lift as compared to the stoop lift. Therefore, the results of this study did not support the hypothesis that an exploration of different lifting movement strategies would elicit movement strategy adaptation to optimize for certain task relevant performance criteria, however this may have been due to limiting factors such as the functional capacity of participants. However, the results of this study do demonstrate how varying task parameters can significantly modulate the biomechanics and energetics of occupational lifting, and thus the resulting preferred lifting technique. Although this study may not have uncovered how an individual's optimal feedback control law may change during occupational lifting when exposed to different movement strategies, it does provide insight into how an individual's preferred lifting movement strategy can be affected by the biomechanical and metabolic exposures experienced due to varying task parameters.

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To my parents, I appreciate your love, support, and encouragement throughout this entire journey. Biomechanics research was not what I had initially imagined myself doing after my undergraduate degree, but thanks to your willingness to provide me the freedom to explore my options, it is the domain I have now fallen in love with.

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## Table of Contents

AUTHORS DECLARATION.....	ii
Abstract.....	iii
Acknowledgments.....	vi
List of Figures.....	x
List of Tables.....	xii
Chapter 1.....	1
The Need to Identifying Biologically Relevant Performance Criteria in MMH.....	1
Chapter 2.....	4
2.1 Overview of Optimal Feedback Control Theory.....	4
2.2 Examples of the Application of Movement Optimality Principles in MMH Posture and Movement Prediction Literature.....	5
2.2.1 Xiang et al., 2010.....	5
2.2.2 Marler et al., 2011.....	8
2.2.3 Xiang et al., 2012.....	9
2.2.4 Song et al., 2016.....	9
2.2.5 Lad, 2018 (MSc Thesis).....	10
2.2.6 Rout et al., 2020.....	11
2.2.7 Summary of Optimization-Based Posture/Movement Prediction Literature.....	13
2.3 Studies of Optimization in Gait.....	14
2.4 Credit Assignment in Movement Strategy Optimization.....	17
2.5 Variables That May Be Biologically Relevant In MMH.....	18
2.5.1 Low Back Flexion/Extension Moment.....	18
2.5.2 Metabolic Cost.....	19
2.6 Effects of Task and Individual Characteristics on Performance Criteria Relevance.....	20
2.7. Literature Review -- Conclusion.....	22
Chapter 3.....	24
Chapter 4.....	26
4.1 Participants.....	26
4.2 Experimental Design.....	26
4.3 Experimental Protocol.....	29

4.3.1 Day One .....	29
4.3.2 Day Two .....	30
4.4 Data Collection and Instrumentation.....	31
4.4.1 Optical Motion Capture .....	31
4.4.2 Gas Flow Analysis System .....	32
4.5 Data Conditioning and Modelling.....	32
4.5.1. Labelling and Gap-filling 3D Motion Capture Data .....	33
4.5.2. Modelling with Visual3D.....	33
4.5.3. Identifying Events .....	35
4.6. Calculation of Biomechanical and Metabolic Outcome Measures .....	37
4.6.1. Peak L4/L5 Sagittal Plane Moments .....	37
4.6.2. Lift Duration .....	37
4.6.3. Squat-Stoop Index .....	37
4.6.4. Metabolic Cost.....	38
4.7. Hypothesis Testing.....	38
Chapter 5.....	39
5.1. Demographics.....	39
5.2. Hypothesis Testing.....	40
5.2.1. Peak Sagittal L4/L5 Moment .....	40
5.2.2. Relative VO <sub>2</sub> Consumption.....	41
5.3. Secondary Analysis .....	42
5.3.1. Ventilation.....	42
5.3.2. Changes within Lifting Bouts .....	44
5.3.3. Squat-Stoop Index .....	45
5.3.4. Lift Duration.....	48
Chapter 6.....	50
6.1. Biomechanical Exposure.....	50
6.2. Metabolic Cost .....	51
6.3. Lifting Movement Strategy .....	53
6.4. Limitations .....	56
Chapter 7.....	59
Bibliography .....	60

Appendix A.....	73
Appendix B.....	74
Appendix C.....	75
Appendix D.....	76

## List of Figures

Figure 1: Figure from Xiang et al., 2010 showing predicted sagittal plane joint angles of various joints relative to mean and 95% confidence range of experimental data.....	7
Figure 2: Animation images from Marler et al, (2011) of predicted lift initiation postures compared to imported experimental posture when lifting a 20 lb box.....	9
Figure 3: Figure from Rout et al., 2020 showing the path of the object simulated from initial position to final position.....	12
Figure 4: Figure from Rout et al., 2020 showing the outputs for the discomfort OF, energy OF, and the MOO at each reference position of the first path of operation.....	12
Figure 5: Figure from Selinger et al. (2019) showing a new step frequency-metabolic cost relationship after activation of a resistive exoskeleton as well as the original relationship .....	16
Figure 6: Visualization of Hypothesized Results.....	24
Figure 7: Flow chart illustrating the order of lifting technique conditions for each exposure condition series.....	27
Figure 8: Birds eye view of the LLHF experimental setup.....	28
Figure 9: Birds eye view of the HLLF experimental setup.....	28
Figure 10: Cluster and marker instrumentation. ....	30
Figure 11: VO <sub>2</sub> Master affixed to a participant retrieved from the VO <sub>2</sub> Manual.....	31
Figure 12: Available VO <sub>2</sub> Master user-pieces.....	32
Figure 13: The start of the lift identified through Visual 3D .....	36
Figure 14: The end of the lift identified through Visual 3D .....	36
Figure 15: Comparison of the mean peak sagittal L4/L5 moments between SS <sub>1</sub> and SS <sub>2</sub> .....	40
Figure 16: Mean peak sagittal L4/L5 moments for the first and last ten lifts averaged across all participants.....	41
Figure 17: Comparison of the mean VO <sub>2</sub> consumption between SS <sub>1</sub> and SS <sub>2</sub> .....	42
Figure 18: The mean ventilation for the last 3-minutes of lifting condition.....	43
Figure 19: Mean VO <sub>2</sub> consumption for each minute of lifting within each lifting bout .....	44
Figure 20: The lifting postures corresponding to a Squat-Stoop Index of 14.7 and 96.1 .....	45
Figure 21: The mean Squat-Stoop Index for the last ten lifts averaged across all participants for each task condition.....	46

Figure 22: The mean peak L4/L5 moment for the last ten lifts for both task conditions plotted against the mean SqStI for the last ten lifts.....	46
Figure 23: The mean VO <sub>2</sub> consumption for the last three-minutes of both task conditions plotted against the mean SqStI of the last ten lifts.....	47
Figure 24: Get Active Questionnaire .....	72
Figure 25: Nordic Questionnaire .....	73

## List of Tables

Table 1: Summary of objective functions applied in the literature.....	13
Table 2: Segment definitions – Identifying the distal/ proximal segment points and calculations of joint center locations.....	34
Table 3: Participant demographics and average load lifted in each task condition.....	39
Table 4: Recorded MVICs between task condition days and their respective percent differences.....	39
Table 5: The means, standard deviations, and ranges for the lift durations of the last ten lifts of each lifting bout.....	49
Table 6: The mean change in relative VO <sub>2</sub> consumption from the third minute of lifting to the last minute of lifting.....	50

# Chapter 1

## Introduction

### **The Need to Identifying Biologically Relevant Performance Criteria in MMH**

Manual materials handling (MMH) tasks are mainly comprised of lifting, lowering, pushing, pulling, and carrying and are a primary driver of musculoskeletal disorders (MSDs) (Punnett & Wegman, 2004). In Canada alone, the cost of MSDs exceeds \$20 billion/year while also posing a burden on the well-being of MMH workers (Patra et al., 2007). By applying principles of ergonomics we can design safer MMH work, preventing many of these injuries. As a proactive ergonomics design approach, MMH movement behavior can be simulated in a virtual environment to identify and design out hazardous MMH tasks before exposing “live” human workers real job tasks. But this means we need to be able to make good predictions about how humans might move to perform MMH tasks within the virtual environment (i.e., in the absence of available motion capture data). Therefore, it is important to improve our fundamental understanding of how humans choose movement strategies when performing occupational MMH tasks to help us proactively design safer MMH work.

In proactive ergonomic design, digital mock-up methods can be used during the design stage to assess the ergonomic feasibility of a job in a more cost-effective manner than traditional physical prototyping design processes (Chaffin, 2005). Digital human models (DHMs) can be used in conjunction with digital mock-ups of jobs to design out MMH-related MSDs risks. DHMs allow users to insert a human avatar into the digital (virtual) workspace, then to predict the motions or postures required to perform defined tasks (e.g. lift box from point A to point B). The user can scale the anthropometrics of the avatar to fit different populations to assess how different people will interact with the same job (Chaffin, 2005). To simulate a defined task, the DHM software predicts and simulates the kinematics of the avatar given a user-defined task goal and any environmental constraints. Based on the predicted avatar kinematics and any user input external forces, a DHM software then performs inverse dynamics calculations to estimate the biomechanical exposures that the avatar experiences (Duffy, 2008). The DHM-based biomechanical exposure outputs can then be used to decide whether the job should be changed to

reduce hazardous exposures. Therefore, DHM alongside digital mockups of jobs offers designers a method to proactively consider the biomechanical exposures experienced by workers'. However, the prediction of biologically plausible postures remains as a challenge for current DHM software (Chaffin, 2005; Paul & Quintero-Duran, 2015).

The design of ergonomically sound workplaces that reduce the biomechanical exposures and subsequent risk of MSDs depends on the ability of DHM software to accurately predict realistic human postures and movements (Chaffin, 2005). Currently, there are two prevalent approaches employed by DHM software to predict human movement: data-driven statistical regression and multi-objective optimization (MOO). Data-driven statistical regression approaches use databases of previously collected motion capture data from participants performing certain tasks. The data is used to drive statistical regression-like models to predict how humans would move given specific task parameters (Faraway & Reed, 2007). Data driven statistical approaches face two important challenges: they can only predict movements for tasks that are included in the motion capture database (i.e., do not extrapolate well); and the quality of the prediction is dependent on the quality of the captured source data. In contrast, optimization-based approaches can predict postures for virtually any task (Abdel-Malek & Arora, 2013), while foundationally adhering to contemporary motor control theory.

Optimization-based posture prediction involves the prediction of postures at instantaneous timepoints by satisfying a set of user-defined objective function(s) (OFs) and constraints. Upon predicting postures at discrete instances in time, interpolation techniques can be used to predict time-series kinematics (Pandy, Anderson & Hull, 1992). Although dynamic (Anderson & Pandy, 2001) or pseudo-dynamic (Thelen, Anderson & Delp, 2003) optimization approaches can be used for continuous optimization-based prediction of movement, the current research focusses on posture prediction at discrete time points, coincident with the current state of the art in DHM for ergonomics application.

The OFs used in DHM refer to the variables that are considered in the mathematical optimization computations. The biological validity of optimization-based posture prediction depends directly upon the biological relevance of these underlying OFs, and their respective weightings that drive the optimization algorithms. In optimization-based posture prediction research, OFs have generally been selected arbitrarily (Latash, 2012). The lack of empirical

evidence to support OF and weighting selections may limit the validity of optimization. In contrast, performance criteria refer to aspects of human movement that the motor control system aims to optimize when coordinating motor performance. Therefore, for a DHM software to effectively predict realistic human movement, the underlying OFs should be aligned with biologically relevant performance criteria.

Optimal Feedback Control (OFC) theory (Todorov & Jordan, 2002) suggests that humans select movement strategies that are optimal to achieve certain task-relevant performance criteria. For example, in the context of gait, research has consistently shown that humans optimize their movement strategies (e.g., stride length, step cadence) to minimize metabolic cost (Ralston, 1958; Selinger et al., 2015; Simha et al., 2019). In the context of MMH, studies suggest that some individuals may optimize MMH movement strategies to minimize biomechanical exposures (Albert et al., 2008; Armstrong & Fischer, 2020; Davis, 1965; Makhoul et al., 2017;). There has also been preliminary evidence to suggest that MMH movement strategies may also be optimized for metabolic cost (Plamondon et al., 2014). However, empirical evidence to support this speculation within a MMH context is limited, a noted gap in our fundamental understanding. Therefore, it is important to explore biomechanical and metabolic relevant performance criteria in the context of MMH movements. Additionally, there is a lack of understanding regarding how task parameters such as load mass or lift frequency interact and influence the weightings of biomechanics and metabolic related performance criteria. For example, biomechanical related performance criteria may be more important to consider in situations where heavier loads are lifted, where metabolic related criteria may be more important in situations where lift frequency is higher. Therefore, the overarching aim of this study is to investigate the biological relevance of biomechanical- and metabolic-based performance criteria during lifting.

## Chapter 2

### Literature Review

This chapter will begin with an overview of OFC theory from a high-level motor control perspective, followed by examples of the application of OFC principles in the context of DHM posture prediction. Finally, previous research regarding human movement strategy optimization will be presented to provide the theory on which the proposed experimental framework is based.

#### 2.1 Overview of Optimal Feedback Control Theory

OFC (Todorov & Jordan, 2002) is a theoretical model of sensorimotor control that aims to explain how the motor control system coordinates the abundant, and often redundant, degrees of freedom of the human musculoskeletal system. OFC theory postulates that movement strategies are selected and adjusted to optimize for certain performance criteria. This is accomplished through a closed-loop system where the motor control system performs online adjustments of motor synergies in response to sensory feedback (Todorov & Jordan, 2002). These motor synergies can be described as “high-level ‘control knobs’ that have invariant and predictable effects on the task-relevant movement parameters” (Todorov & Jordan, 2002). This concept of high-level motor control is supported by experimental data collected during grasping (Santello & Soechting, 2000), pointing (Tseng et al., 2002) and reaching (Scott et al., 2015) tasks.

Motor synergies are only adjusted to correct and/or optimize task-relevant aspects of performance (Todorov & Jordan, 2003). Task-relevant aspects of performance refer to the specific variables or factors that directly influence the achievement of a task goal. Conversely, task-irrelevant aspects of performance have little influence on the achievement of a task goal. Task relevant vs. task-irrelevant aspects of performance can be observed in reaching to grasp a bottle of water. When reaching towards a bottle, small changes in the medio-lateral direction of hand trajectory would significantly affect a person’s ability to grasp the bottle. Meanwhile, due to the shape of a standard water bottle, small changes in the infero-superior direction of hand trajectory would have less impact on one’s ability to grasp the bottle. In this case, the motor control system is likely to deem the medio-lateral dimension as more task-relevant than the infero-superior dimension. Therefore, the motor control system would control for medio-lateral deviations in hand trajectory much more tightly than infero-superior deviations. This phenomenon is encapsulated by the minimal intervention principle (Todorov & Jordan, 2003), which suggests that variability in

movement trajectories is only controlled for when it affects task-relevant aspects of performance. In turn, aspects of movement that are deemed as task-irrelevant by the motor control system will exhibit more variability than those that are task-relevant (Todorov & Jordan, 2003).

Through the lens of OFC theory, only task-relevant aspects of performance are tightly controlled when performing a task. In contrast, task-irrelevant aspects of performance are less controlled for. In theory, one could infer what aspects of performance are deemed task-relevant by the motor control system by identifying the variables that improve (e.g. decreasing low back moment) as a person gains experience with a task. These variables would likely represent aspects of the task that are considered as relevant performance criteria by the motor control system in the context of OFC theory. These variables would also represent biologically relevant OFs in the context of optimization-based posture prediction.

## **2.2 Examples of the Application of Movement Optimality Principles in MMH Posture and Movement Prediction Literature**

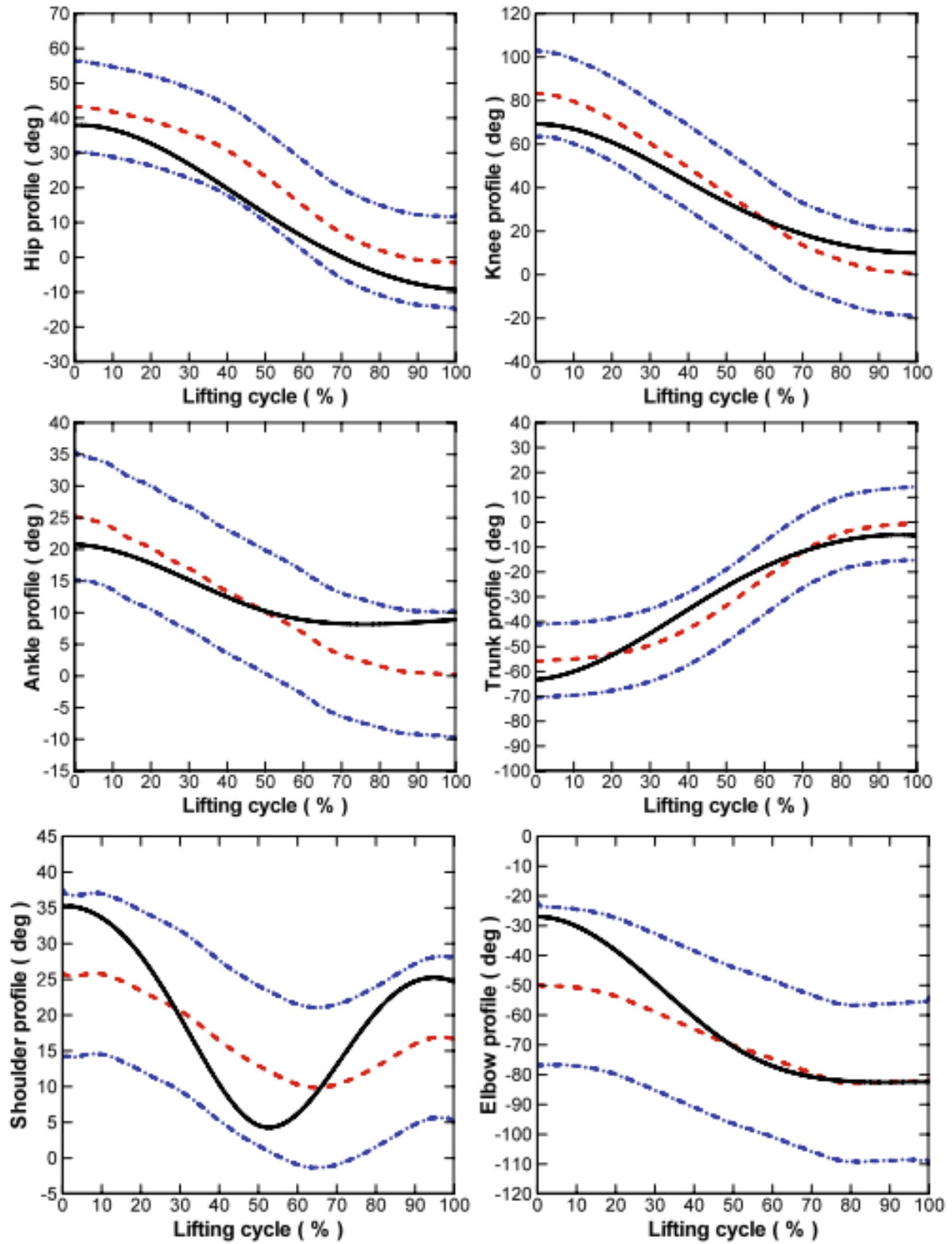
In the past decade there have been several studies regarding optimization-based prediction of MMH posture and movement. They are briefly summarized in the following sub-sections.

### **2.2.1 Xiang et al., 2010**

In this study, a MOO approach was utilized to simulate the process of lifting a box from knee to shoulder height using a 55 degree-of-freedom biomechanical model. The OFs considered were the minimization of dynamic effort and the maximization of dynamic stability. Dynamic effort was defined as the integral of the sum of squared joint torques, while dynamic stability was defined as the squared distance between the zero moment point and the base of support boundary. The weights assigned to these OFs varied from 0% to 100% in 10% intervals. The subsequent predicted kinematics associated with each weighting configuration were then compared to experimental data to identify the most suitable OF weighting configuration.

After evaluating different configurations, an optimal weighting of 90% dynamic effort and 10% dynamic stability was determined. The predicted sagittal joint angles of the shoulder, elbow, trunk, hip, and ankle fell within a 95% confidence interval of the experimental data collected from five subjects. However, when examining the results qualitatively, the predicted joint angle waveforms often approached the boundaries of the 95% confidence interval and displayed

subjective differences in the overall shape of the curve (Figure 1). The authors acknowledged that their predictive model had difficulties in accurately predicting shoulder postures. This difficulty may be attributed to the nature of the OFs employed in this study. Given the substantial biomechanical demands on the glenohumeral joint in this study, it is reasonable to assume that the motor control system prioritizes shoulder joint moments to a greater extent compared to other, less strained joints. Hence, it may be advantageous to incorporate an OF that specifically considers joints experiencing high relative demands, rather than all joints, when predicting postures in MMH tasks.

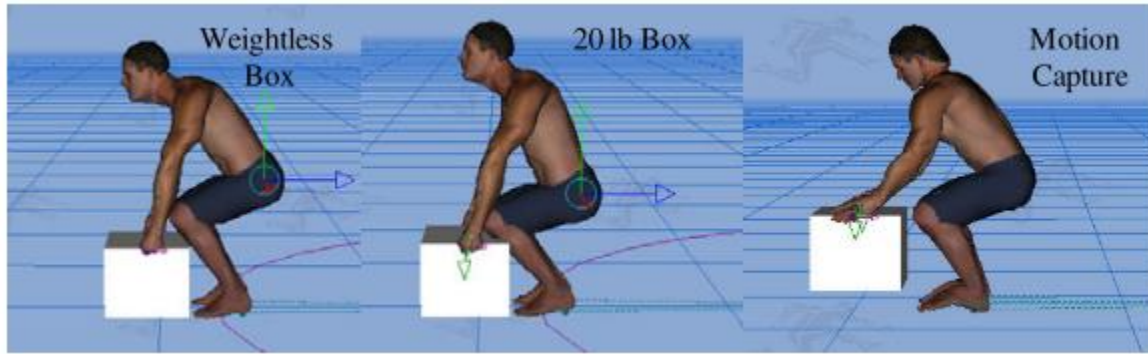


**Figure 1:** Figure from Xiang et al., 2010 showing predicted sagittal plane joint angles (black) of various joints relative to mean (red) and 95% confidence range of experimental data (blue)

### **2.2.2 Marler et al., 2011**

In their study, Marler et al., (2011) utilized a MOO approach in conjunction with the Santos Pro model (SantosHuman Inc. Coralville, IA) to simulate a box lift. The OFs considered were the minimization of the maximum relative joint torque demand in the body and the minimization of joint displacement from neutral, defined as an upright standing posture with arms straight down parallel to the torso. The weightings assigned to the maximum relative joint torque demand OF and the joint displacement OF were 75% and 25% respectively. The authors found that their MOO approach produced postures that closely resembled those observed through motion capture. However, a comparison of predicted postures and experimentally recorded postures at the initiation of the lift revealed a key difference (Figure 2), where the predicted postures resulted in the box hitting the avatar's knees.

Visually, the predicted posture for the 20 lb. box lift obtained through MOO generally matched the posture captured from motion capture, except for the shoulder posture (Figure 2). This discrepancy may be attributed to factors like those discussed in Section 2.2.1. The applied OF only considers a single joint, specifically the joint experiencing the highest torque relative to its torque capacity. However, in this task, both the shoulder and hip joints are likely experiencing high relative joint demands. By considering only one joint, the demands of the other joint may be overlooked. If the hip joint experiences the greatest relative joint torque demand, the applied OF would not account for the relative demand at the shoulder. The resulting predicted posture would most likely not be realistic at the shoulder, as seen in Figure 2, and the calculated shoulder kinetics would also be inaccurate. A more biologically relevant approach may involve an OF that considers multiple joints experiencing high relative demand.



**Figure 2:** Animation images from Marler et al. (2011) of predicted lift initiation postures compared to imported experimental posture when lifting a 20 lb box.

### 2.2.3 Xiang et al., 2012

The objective of this study was to evaluate the predictions made for a box lift movement using a single OF optimization approach combined with a 55 degree-of-freedom biomechanical model. Four different OFs were considered: dynamic effort, dynamic stability, the minimization of integrated low back shear joint forces and the minimization of integrated low back compressive joint reaction forces. The definitions of dynamic stability and effort can be found in Section 2.2.1. The OFs of dynamic stability and the minimization of shear joint reaction forces predicted stoop lifts where hip flexion/extension were the primary drivers of the lift. The OF for dynamic effort predicted a squat technique where the primary driver of the lift was knee flexion/extension. Finally, the minimization of compressive reaction forces resulted in a lifting strategy where the avatar initially flexed at the hips to reach the box, then flexed at the shoulder to slightly raise the box, and then finally extended at the hips to fully lift the box. Using a single OF optimization approach, the authors' results imply that whether a person tends to use a more stoop-like or squat-like lifting movement strategy depends on what performance criteria their motor control system is aiming to optimize for; an important finding to inform the current study.

### 2.2.4 Song et al., 2016

In this study, a hybrid MOO approach was used to predict box lifting kinematics by using two OFs: the minimization of physical effort and the maximization of load motion smoothness. Physical effort was defined as the squared sum of ratios between individual joint moments and their corresponding torque capacities. Load motion smoothness was defined as the minimization

of end-effector (hand) jerk. Their hybrid MOO approach incorporated experimental data by setting boundary constraints on joint angles based on collected kinematic data. Separate sets of experimental data were collected from older (55+ years old) and younger (20-30 years old) participants. The researchers investigated different OF weighting configurations by adjusting the weightings so that each OF was weighted from 0% to 100% in 10% increments. In young participants, a 90% physical effort and 10% load motion smoothness weighting yielded the closest agreement with experimental data. Conversely, in older participants, a 10% effort and 90% smoothness weighting yielded the best agreement with experimental data. The experimental data revealed that younger participants tended to exhibit greater trunk flexion angles and lift velocities compared to older participants. The authors suggest that younger individuals adopt this strategy to reduce lift duration and metabolic cost (Maduri, Pearson & Wilson, 2008), while older individuals choose their strategy to minimize biomechanical exposure on the low back given their increased risk of low back pain (Heiden et al., 2013). These findings, alongside those discussed in 2.2.3 highlight that the relevance of a specific objective function can be influenced by individual characteristics.

### **2.2.5 Lad, 2018 (MSc Thesis)**

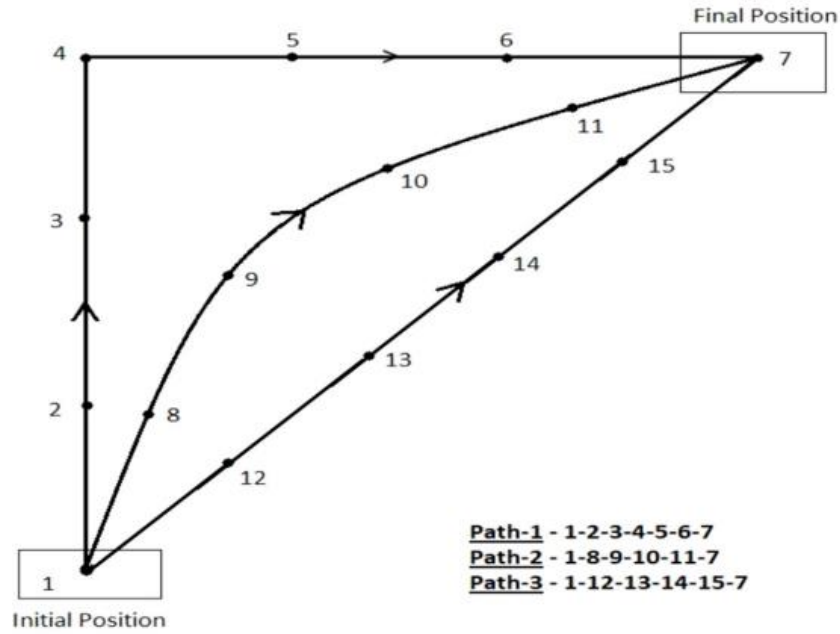
In this study, two widely used DHM software programs, Siemens Jack (Siemens AG, Munich, Germany) and Santos Pro, were employed to predict postures in a healthcare patient handling scenario. The task involved rolling a supine patient in a hospital bed, and the DHM predicted kinematics and kinetics were compared to outputs from a lab-based rigid link model to evaluate their accuracy. The Santos MOO approach incorporated various OFs including joint displacement from a neutral standing posture, change in segment potential energies, discomfort, effort, and visual displacement (Abdel-Malek et al., 2007; Marler et al., 2009). Discomfort was minimized by prioritizing sequential distal-to-proximal segment motion, assuming neutral postures whenever possible, and avoiding extreme ranges of motion in articulating joints. Visual displacement is minimized by positioning the head of the avatar to “look” at the object being handled (Marler et al., 2006). Statistically significant differences were observed in sagittal trunk angles, sagittal plane L4/L5 and glenohumeral moments between the predictions of Santos Pro and the lab-based model. Modest differences were also observed in predicted glenohumeral joint angles. These findings suggest that the set of OFs used in the DHM predictive model may not be aligned with the performance criteria considered by the participants’ motor control systems.

Perhaps, in this context, it may have been more appropriate to incorporate OFs that directly consider the biomechanical exposures at the low back and shoulders as those joints experience high biomechanical exposures during patient handling (Budarick, Lad & Fischer, 2020).

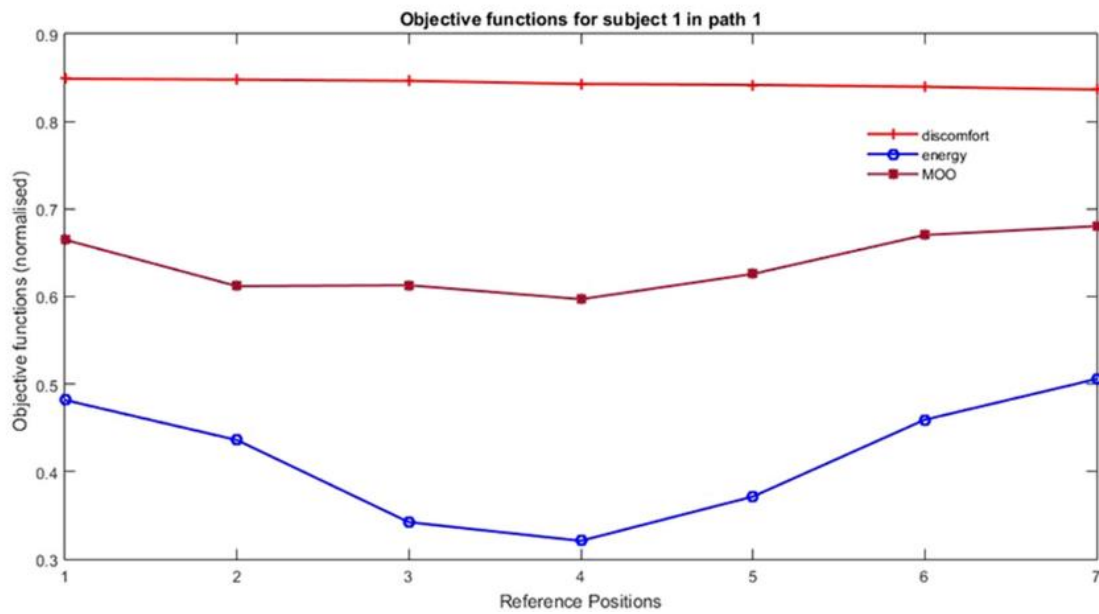
### **2.2.6 Rout et al., 2020**

This study applied a MOO approach with a 20 degree of freedom biomechanical model to simulate posture in an assembly process. The considered OFs were the minimization of joint discomfort and the minimization of energy expenditure. This study defined joint discomfort as the avoidance of articulating joints to near their end range of motion while energy expenditure was defined as the sum of mechanical power of muscle and basal metabolic rate. The lifting scenario comprised of lifting a 3 kg object once, and it was simulated with two subjects having weight 75 kg and 58 kg respectively. The authors established three paths of operation that the simulations would have to follow due to the nature of assembly work having set starting and endpoints (Figure 3). Along these paths, posture was predicted at predetermined reference positions to determine objective function outputs. Postures for each path were first simulated using only the joint discomfort or energy expenditure OF, then finally with both OFs.

It was found that when only considering the joint discomfort or energy expenditure function, the output curve lay on the top or bottom of the curve respectively (Figure 3). As expected, when MOO was used to consider both OFs, the output curve lay in between the discomfort and energy functions (Figure 4). The authors suggest that in the optimization of discomfort, we can neglect the total energy expended. Similarly, in the optimization of energy expenditure we can neglect joint discomfort. It was also observed that when the energy expenditure decreased, the joint discomfort would increase, or vice versa. These results suggest that an OF that considers the energy expenditure while performing MMH tasks could be a viable option, and that there are potential trade-offs between the minimization of energy expenditure and other OFs such as the minimization of joint discomfort; another important insight to inform the current study.



**Figure 3.** Figure from Rout et al., 2020 showing the path of the object simulated from initial position to final position.



**Figure 4:** Figure from Rout et al., 2020 showing the outputs for the discomfort OF (red), energy OF (blue) and the MOO (dark red) at each reference position of the first path of operation.

## 2.2.7 Summary of Optimization-Based Posture/Movement Prediction Literature

The aforementioned studies applied a variety of OFs which are summarized in Table 1. However, there remains a lack of consensus regarding which OFs are most biologically relevant in the context of MMH. Furthermore, many of these studies encountered challenges in accurately predicting shoulder postures. While some studies considered relative joint demands, they either examined these demands across all joints or focused solely on the joint with the highest relative demand. A more biologically relevant OF may be one that specifically aims to minimize the demands on multiple joints experiencing high relative demands. Additionally, it is important to note that these studies did not provide empirical evidence to support their selection of the applied OFs. This emphasizes the need for *in vivo* studies that can offer empirical support for the selection of biologically relevant OFs in MMH by enhancing our understanding of the factors influencing movement strategy selection.

Author, Publication Year	Considered OFs	Definition
Xiang et al., 2010	Dynamic Effort	The integral of the sum of square joint torques
	Dynamic Stability	The squared distance between the zero moment point and the base of support boundary
Marler et al., 2011	Maximum relative joint torque	The relative joint torque at the joint experiencing the highest relative demand
	Joint displacement from neutral	The joint displacement from neutral standing posture, or from a neutral posture defined by the user
Xiang et al., 2012	Dynamic effort	The integral of the sum of square joint torques
	Dynamic stability	The squared distance between the zero moment point and the base of support boundary
	Low back shear joint reaction force	The minimization of the maximum shear force at spine joint
	Low back compression joint reaction force	The minimization of the maximum pressure force at spine joint
Song et al., 2016	Physical effort	The squared sum of ratios between joint moments and their corresponding torque capacities
	Load motion smoothness	The minimization of end-effector (hand) jerk

Lad, 2018	Joint displacement from neutral	The joint displacement from neutral standing posture, or from a neutral posture defined by the user
	Change of segment potential energies	The minimization of the potential energy of segments represented as lumped masses
	Discomfort	The prioritization of sequential distal-to-proximal segment motion, assuming neutral postures whenever possible, and avoiding extreme ranges of motion in articulating joints
	Visual Displacement	Positioning the head of the avatar to “look” at the object being handled
	Dynamic Effort	The integral of the sum of square joint torques
Rout et al., 2020	Joint Discomfort	The avoidance of articulating joints to near their end range of motion
	Energy Expenditure	The sum of mechanical power of muscle and basal metabolic rate

### 2.3 Studies of Optimization in Gait

While there is limited empirical evidence to support the biological relevance of specific OFs in MMH, extensive research exists regarding optimal control in gait. Also, the extensive body of research regarding optimal control in gait may help to inform a research paradigm to explore similar questions in an MMH context. Research has consistently shown that individuals tend to walk in ways that minimize metabolic cost (Abram et al., 2019; Minetti & Alexander, 1997; Ralston, 1958). Notably, there is strong evidence to support that people naturally select step frequencies that minimize metabolic cost (Minetti & Alexander, 1997; Umberger & Martin, 2007; Zarrugh, Todd, & Ralston, 1974). Moreover, recent research has shown that individuals can adapt their motor control strategy to optimize step frequency for metabolic cost within minutes when the relationship between step-frequency and metabolic cost is altered (Selinger et al., 2015). However, it is important to note that most people do not spontaneously initiate movement strategy optimization in response to changes in the step frequency-metabolic cost relationship (Selinger et al., 2019; Wong et al., 2019). Instead, exposure to a wide range of movement strategies is often required for individuals to “learn” and adapt their optimal movement strategy (Selinger et al.,

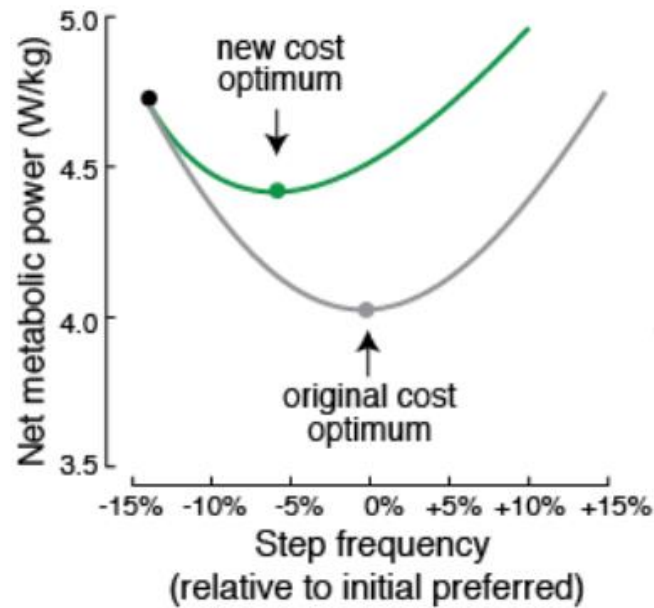
2019; Wong et al., 2019). This paradigm has been successfully applied in studies involving gait, where participants were exposed to varied step frequencies (Selinger et al., 2015; Selinger et al., 2019; Wong et al., 2019). However, in the context of MMH, identifying an analogous movement parameter to step frequency presents a challenge.

Selinger et al., (2019), Selinger et al., (2015), and Wong et al., (2019) applied a research paradigm that involved altering the relationship between step frequency and metabolic cost during walking. They utilized a lower limb exoskeleton to modify this relationship by applying resistive torques as a function of step frequency. Consequently, the once-optimal step frequency for metabolic cost minimization became suboptimal due to the perturbations induced by the exoskeleton (Figure 5). This paradigm allowed for the examination of the optimization process by observing participants' adjustments, or lack thereof, to their self-selected step frequencies in response to the novel step frequency-metabolic cost relationship.

Selinger et al., (2019) reported that only six out of thirty-six participants in their study exhibited spontaneous initiation of step frequency optimization during treadmill walking. These spontaneous initiators demonstrated greater movement variability during baseline treadmill walking compared to non-spontaneous initiators. Selinger et al., (2019) suggest that increased movement variability is positively correlated with the likelihood of spontaneously optimizing movement strategy, as it allows for a broader range of movement strategies and subsequent performance outcomes to be sampled. Therefore, in the context of MMH, individuals displaying higher movement variability may be more likely to initiate spontaneous movement strategy optimization.

In the experiment done by Selinger et al., (2015), optimization was successfully elicited in non-spontaneous initiators by explicitly prescribing variations in relevant movement parameters. This was achieved through an exploratory phase where participants synchronized their steps with an auditory metronome set to frequencies approaching the new metabolically optimal step frequency. After this exploratory phase, participants were allowed to self-select their step frequency, and the non-spontaneous initiators adapted their step frequencies to converge on the new optimal step frequency. These findings highlight the effectiveness of encouraging broad sampling of movement strategies through prescribed movement patterns to foster movement strategy optimization. Therefore, studies aiming to promote movement strategy optimization

should include a phase that encourages participants to explore along relevant movement dimensions.



**Figure 5:** Figure from Selinger et al. (2019) showing a new step frequency-metabolic cost relationship (green) after activation of a resistive exoskeleton as well as the original relationship (grey)

To investigate whether energy optimization involves “implicit processing” (occurring automatically with minimal cognitive attention) or “explicit processing” (occurring consciously with an attention-demanding strategy), McAllister et al., (2021) applied a dual-task paradigm to the previous experimental design of Selinger et al., (2015). Their dual-task experimental design had participants walk with a resistive lower limb exoskeleton (Selinger et al., 2015; Selinger et al., 2019) while performing a ‘one-back’ audio tone discrimination task. They found that adding this secondary, cognitively demanding, explicit task did not prevent energy optimization in participants. Adaptation magnitudes and rates were similar to those seen in Selinger et al., (2015) and Selinger et al., (2019), and performance of the secondary tone discrimination task did not worsen when participants were adapting toward their new energy optima. These findings suggest that even when explicit awareness exists, it may not affect one’s ability to discover the energy optima. The potential benefit that energy optimization involves implicit processing is that attentional resources can be directed toward other movement objectives such as accuracy or stability. McAllister et al., (2021) suggest that these explicit demands may act as constraints, while energy optimization proceeds implicitly within these bounds. Therefore, in the context of MMH,

where an individual's attentional resources may be directed toward other task-relevant aspects of performance, it is still likely that the implicit system is still navigating for an energy optimal solution.

Movement variability, whether inherent or prescribed, has been shown to be related to the optimization of movement strategy (Selinger et al., 2019; Wu et al., 2014). However, the specific magnitude of variability required to consistently initiate optimization remains unclear. Wong et al., (2019) discovered that an exploratory phase involving walking on outdoor paths with varying slopes and curvatures did not provide a sufficient sampling breadth of the step frequency-metabolic cost relationship to trigger spontaneous optimization. Therefore, a study aiming to promote movement strategy optimization in a specific task, such as MMH, should incorporate an exploratory phase that introduces a dimension of movement with a significantly greater degree of variation than the natural trial-to-trial variability. This can be achieved by explicitly modifying participants' movement strategies, as demonstrated in Selinger et al., (2019) where participants synchronized their steps with a metronome. In the proposed study, sampling of a range of movement strategies will be encouraged during exploratory trials by prescribing squat and stoop techniques.

## **2.4 Credit Assignment in Movement Strategy Optimization**

Credit assignment refers to the motor control system's process of determining the relationship between changes in movement and the resultant performance criteria outputs (Wolpert et al., 2011). This process plays a crucial role in movement strategy optimization as it enables the motor control system to identify which movement dimension should be explored to improve performance. For instance, in the study conducted by Selinger et al., (2019), the exploration primarily focused on the movement dimension of step frequency.

In movement strategy optimization, it is not only important to determine which movement dimensions to explore but also the direction of exploration along these dimensions. Selinger et al., (2019) found that during an exploratory phase with a novel step frequency-metabolic cost relationship, participants who were prescribed step frequencies closer to the new optimum tended to converge on the new optimum when given the freedom to self-select their movement strategy. On the other hand, participants who were prescribed step frequencies further from the new optimum did not adapt to the new optimum, but instead returned to their initial, sub-optimal self-

selected step frequency. Therefore, an exploratory phase aiming to promote movement strategy optimization should guide the exploration such that the direction of exploration is towards the optimum.

In the context of MMH, where specific performance criteria are still unknown, it is challenging to design a protocol that encourages exploration along relevant dimensions of movement. However, based on biomechanical and metabolic considerations (Sections 2.5.1 & 2.5.2), stoop and squat lift techniques have been suggested as optimal for different measures. Garg & Herrin (1979) also reported relative advantages of squat and stoop lift techniques in terms of biomechanics and metabolic cost, respectively. Therefore, it is likely that participants will be guided towards the optimum along a dimension of movement in at least one of the lifting technique conditions.

## **2.5 Variables That May Be Biologically Relevant In MMH**

Based on the variables that have been previously applied as OFs in MMH posture/movement prediction contexts (Table 1), the following variables will also be considered as potential biologically relevant MMH performance criteria in the proposed thesis.

### **2.5.1 Low Back Flexion/Extension Moment**

Research has consistently shown that when lifting in a MMH context, both novice (Burgess-Limerick et al., 1995) and expert lifters (Scholz, 1993) perform knee extension first, followed by trunk extension. The selection of this inter-joint coordination pattern may indicate that low back biomechanical exposures such as joint moments, low back compression, and/or low back shear are biologically relevant performance criteria. This pattern is thought to be influenced by the potential for injurious magnitudes of low back biomechanical exposures in the initial phase of lifting, when load and body segment accelerations are at their greatest (Davis et al., 1965). The distal to proximal pattern of inter-joint coordination delays trunk extension and reduces the moment arm of the load relative to the low back prior to initiating trunk extension. Thus, an improved mechanical advantage of the lift can be observed, resulting in reduced low back moments as well as lumbar compression and shear (Albert et al., 2008).

Simulation results based on optimization models by Xiang et al., (2012) also support the selection of distal to proximal lifting strategies for minimizing low back biomechanical exposures.

When minimizing compressive low back reaction forces is used as the OF, simulations predict lifts that are initiated by shoulder extension and are followed by trunk extension. Therefore, the simulated lifting strategies follow the same distal to proximal pattern of inter-joint coordination reported by Albert et al., (2008).

While low back compression has been considered as a biologically relevant performance criterion, it is unlikely to be the primary determinant of movement strategy in a MMH context. Rather, it is probable that it decreases as a result of being related to another variable. This is because psychophysical perception of load is not influenced by spine compression magnitude (Chaffin & Page, 1994; Thompson & Chaffin, 1993). The process of movement optimization requires online feedback regarding task performance (Todorov & Jordan, 2002). Without sensory feedback of spine compression, it is unlikely that the motor control system receives the online afferent feedback required to optimize movement strategy based on direct consideration of this variable. In contrast, sagittal plane lumbar spine moments have been shown to influence perceived psychophysical loads, suggesting that low back moment minimization may be a primary determinant of movement strategy and a relevant performance criterion in MMH movement optimization (Fischer & Dickerson, 2014; Jorgensen et al., 1999; Kuijer et al., 2012). Therefore, while there is speculation that movement strategy selection may be optimized for the minimization of low back compression, it may be more likely that the unperceived low back compression is reduced as a by-product of the minimization of perceived low back moment.

### **2.5.2 Metabolic Cost**

The stoop and squat lift are commonly used as classifications for lifting techniques. Stoop lifting is reported to be more efficient from a metabolic standpoint (Garg & Herrin, 1979; Hagen et al., 1993; Hagen et al., 1994; Straker, 2003; Welbergen et al., 1991) while squat lifting is generally reported to result in lower magnitudes of shear force (Potvin et al., 1991), moments (Dolan et al., 1994a) and passive tissue stress (Dolan et al., 1994b; McGill & Kippers, 1994) at the low back. It is important to note that stoop and squat lifts exist on a continuum rather than being strictly binary. The Lifting Index (LI) developed by Burgess-Limerick & Abernathy (1997), and the Stoop-Squat Index (SqStI) developed by Schmid (2022) both provide quantitative measures to determine the lifting technique's position on the spectrum. The LI considers the ratio of knee flexion to the sum of ankle, hip, and lumbar flexion. An LI score closer to one represents a more squat-like technique

and an LI score closer to zero indicates a more stoop-like technique. The SqStI describes the proportion between trunk forward lean and lower extremity joint flexion, with possible values ranging from zero (full squat) to one hundred (full stoop). In contrast to the LI that requires a measure and summation of multiple joint angles, the SqStI is calculated based on the vertical displacement of the C7 spinous process and the hip joint center, thus providing a less computationally intense method to assess lifting movement strategy (Bangerter et al., 2024).

In untrained lifters, the preference for stoop-like or squat-like techniques is mixed in the literature. Albert et al., (2008) observed untrained lifters employ a stoop-like technique ( $LI = 0.40 \pm 0.08$ ) when lifting crates from floor to waist height with a load scaled to 20% of their maximum capacity. In contrast, Burgess-Limerick et al., (1995) observed untrained lifters use a more squat-like technique ( $LI = 0.58 \pm 0.16$ ) during a repetitive lifting task from floor to shoulder height with various load masses ranging from 2.5 kg to 10.5 kg. Similarly, Burgess-Limerick & Abernathy (1997) found that untrained lifters exhibited a more squat-like technique ( $LI = 0.59 \pm 0.17$ ) when lifting loads of 2.5 kg or 6.5 kg from different starting heights. Burgess-Limerick & Abernathy (1997) reported that LI scores remained consistent regardless of the starting lift height. Across these studies, untrained lifters consistently adopted a “semi-squat” technique that fell between pure squat and stoop techniques. Straker (2003) found that evidence in support or against the semi-squat technique was less common than both the squat and stoop techniques. Straker (2003) found that the potential advantage of a semi-squat was that it was possibly a “natural” movement pattern that was a good compromise between a stoop or a squat. This, along with the reported advantages and disadvantages of a pure squat and stoop technique, could suggest that the motor control system seeks to compromise between optimizing for metabolic cost and the minimization of low back biomechanical exposures during lifting.

## **2.6 Effects of Task and Individual Characteristics on Performance Criteria**

### **Relevance**

The tendency for individuals to optimize lifting strategy for either metabolic cost or biomechanical exposure might depend on individual characteristics and task requirements. For instance, in a study done by Song & Qu (2014), it was found that healthy older adults (55+ years old) exhibited less trunk flexion and slower lift velocities compared to younger healthy adults (20-30 years old). Decreasing trunk flexion and lifting velocity would likely reduce low back

biomechanical exposures (Gregory et al., 2009; Bush-Joseph et al., 1988; Lindbeck & Arborelius, 1991; Marras et al., 1993). However, this lifting strategy may have resulted in higher metabolic costs due to increased lift durations (Maduri et al., 2008). Considering the decreased load tolerance of the spine with increased age (Jager, 2018), it seems logical that older adults would prioritize the minimization of low back biomechanical exposure over metabolic cost. In a different study done by Cashaback & Cluff (2015), they found a shift in OF weighting to favor joint stability at the expense of energy efficiency in healthy young males performing a fatiguing elbow flexion protocol. Although the proposed research does not aim to investigate the effects of muscle fatigue on OF weighting, this finding does demonstrate how the motor control system can adjust its weighting of OFs in real-time throughout the same task depending on what performance criteria it deems as most relevant.

How the motor control system balances between metabolic cost and low back biomechanical exposure is most likely affected by the individual's prior experiences. In young, untrained lifters, increases in load mass are related to the adoption of a more stoop-like lifting technique (Schipplein et al., 1990). This may have the effect of reducing the muscular effort required and delaying potential fatigue (Burgess-Limerick et al., 1995) at the expense of greater low back biomechanical exposures (Dolan et al., 1994a). Untrained lifters also tend to adopt stoop techniques when lifting from floor to increasing heights (Burgess-Limerick et al., 2001). Therefore, it seems that as the relative demands of the lift increase (heavier load or greater lift height), untrained lifters tend to adopt more stoop-like lifting strategies. This tendency may be an unconscious adaptation to reduce metabolic costs or to decrease the relative joint moment demands by utilizing the trunk extensors' high strength capacity (Schibye et al., 2001). In contrast, during paramedic lifting tasks, female paramedics choose lifting strategies that minimize the biomechanical exposure at the spine at the expense of increased muscular effort (Makhoul et al., 2017). Makhoul et al., 2017 suggest that this lifting strategy is an adaptation to the high demands of paramedic lifting, where not minimizing biomechanical exposures would lead to a high risk of injury. Similarly, expert male manual materials handlers maintain more neutral, upright trunk postures to reduce biomechanical exposures (Plamondon et al., 2014). These results align with those of Marras et al., (2006) who found that expert MMH workers had lower low back biomechanical exposures than novice lifters over eight hours of repetitive, asymmetric lifting with a variety of loads and frequencies. Overall, an individual's previous experience and training appear

to influence whether they prioritize low back biomechanical exposure or metabolic cost, with task characteristics also playing a role.

Differences regarding the LI in the work done by Albert et al., (2008) and Burgess-Limerick & Abernathy could be attributed to variations in load mass and/or destination height in their experimental setups. Lift initiation height may (Burgess-Limerick et al., 2001), or may not (Burgess-Limerick & Abernathy, 1997) affect LI, but load mass has been shown to significantly influence lifting technique (Burgess-Limerick & Abernathy, 1997b; Frost et al., 2015). Additionally, lift frequency may also play a role in the optimization of lifting strategy. Although it does not significantly affect low back biomechanical exposure during repetitive lifting (Marras et al., 2006), it does influence the metabolic efficiency of lifts (Welbergen et al., 1991).

## **2.7. Literature Review -- Conclusion**

Based on the literature review conducted, it can be concluded that DHMs serve as an effective tool that designers can use to facilitate proactive ergonomics. By predicting human posture, jobs can be assessed for their safety before any physical prototyping is needed. However, DHM software often struggles to accurately predict realistic human behavior, resulting in unnatural postures or physically impossible limb position. This reveals an underlying gap in our fundamental understanding of how humans select different movement strategies in an occupational context. The current literature highlights what variables DHM software have used to optimize human posture prediction virtually, but little empirical work has been done to investigate whether these variables are truly considered during occupational tasks. Therefore, to accurately predict human posture in a virtual environment, we must first understand the process in which humans select different movement strategies during these occupational tasks.

OFC theory provides a framework to begin explaining why individuals choose specific movement strategies in different contexts. OFC theory suggests that humans move in ways that optimize for certain task-relevant performance criteria, meaning that for any given movement, there are likely a set of variables that we control for that determine whether that movement is deemed “successful”. These variables can also be referred to as determinants of movement strategy. This model has been leveraged to study the optimal control of gait and has produced significant evidence that through movement exploration, humans will adjust their movement strategies to minimize metabolic cost in walking. However, little empirical work has been done

to uncover the underlying determinants of movement strategy selection in occupational tasks such as lifting. If we can deepen our understanding of these determinants of movement behaviour, we can then inform more realistic human posture prediction. Therefore, the purpose of this thesis was to investigate the determinants of occupational lifting movement strategy by using a similar research paradigm from work done in the optimal control of gait.

# Chapter 3

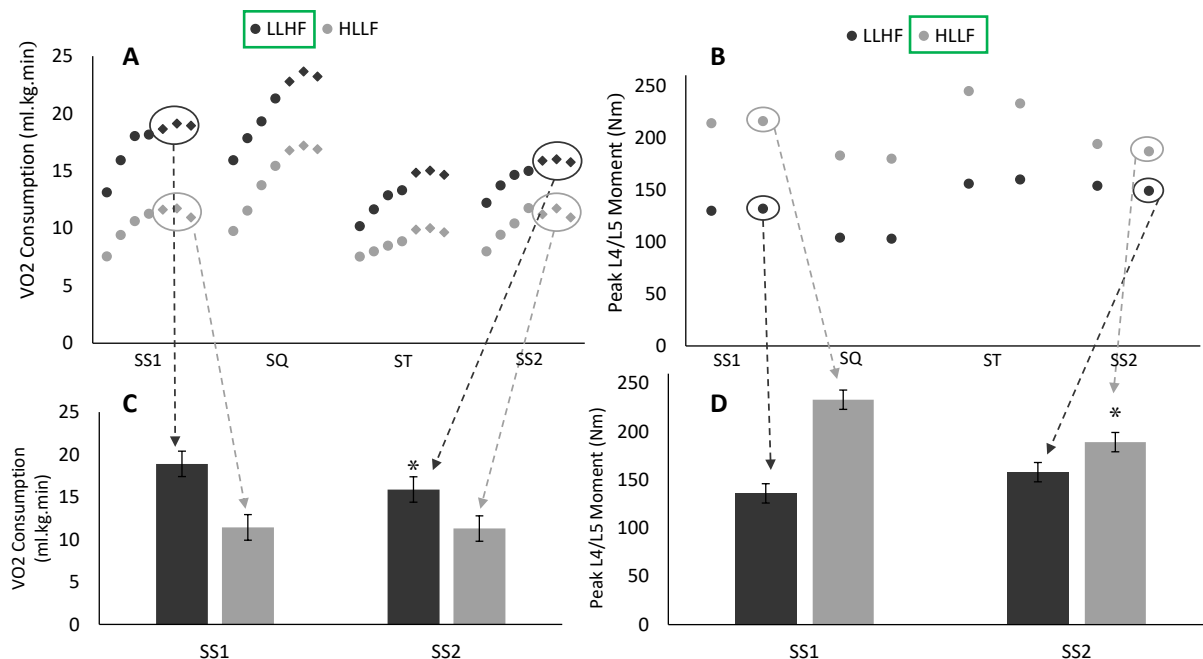
## Research Questions and Hypotheses

### 3.1 Research Question

In untrained lifters, do different levels of task characteristics (high-load low-frequency condition and low-load high-frequency condition) affect biomechanical or metabolic cost exposure variables before and after an exploration period of the “biomechanical exposure landscape”?

### 3.2 Hypothesis

In untrained lifters, biomechanical exposure variables will be significantly lower in the high-load low-frequency (HLLF) condition post exploration (Figures 6B and 6D), and metabolic cost variables will be significantly lower in the low-load high-frequency (LLHF) condition post exploration (Figures 6A and 6C).



**Figure 6:** Visualization of Hypothesized Results

**(A)** Hypothesized results for the average  $VO_2$  consumption each minute for the HLLF and LLHF conditions in pre-exploration, exploration phase (require participants to squat and stoop to experience a range of metabolic and biomechanical sensations), and post-exploration stages. The average of the last 3 minutes of each stage (denoted by diamonds) will be used to compare

*between pre-exploration and post-exploration. Dashed lines indicate that means from the last 3 minutes will be used as outcome measures.*

**(B)** *Hypothesized results for the average peak sagittal L4/L5 moment of the first 10 lifts, middle 10 lifts, and last 10 lifts for the HLLF and LLHF conditions in pre-exploration, exploration phase (require participants to squat and stoop to experience a range of metabolic and biomechanical sensations), and post-exploration stages. Only the average of the last 10 lifts will be used to compare between pre-exploration and post-exploration. Dashed lines indicate that means from the last 3 minutes will be used as outcome measures.*

**(C)** *Hypothesized results for the comparison of average  $VO_2$  consumption in the last 3 minutes between pre-exploration and post-exploration for the HLLF and LLHF conditions. We anticipate a lift condition main effect, where  $VO_2$  consumption will be higher during the LLHF condition relative to the HLLF condition and a time by lift condition interaction where  $VO_2$  consumption will be lower following the exploration period but only during the LLHF condition.*

**(D)** *Hypothesized results for the comparison of average peak sagittal L4/L5 moment of the last 10 lifts between pre-exploration and post-exploration for the HLLF and LLHF conditions. We anticipate a lift condition main effect, where average peak sagittal L4/L5 moment will be higher during the HLLF condition relative to the LLHF condition and a time by lift condition interaction where average peak sagittal L4/L5 moment will be lower following the exploration period but only during the HLLF condition.*

This study will strengthen our fundamental understanding about how lift characteristics inclusive of load mass and lift frequency may interact with how a lifter may move to minimize biomechanical exposure and metabolic cost.

## Chapter 4

### Methods

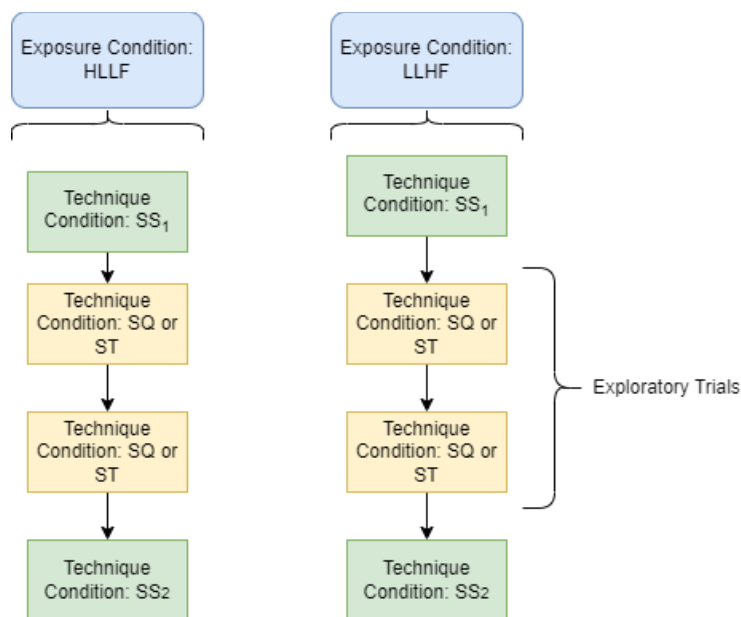
#### 4.1 Participants

Twenty-six participants (11 male, 15 female) were recruited from the University of Waterloo student population. A sex-balanced sample was intended for representativeness but not achieved as not enough male participants were willing to participate within the reasonable recruitment window of six months. However, a planned sex comparison was not within the scope of this current study. This sample size was determined through an a priori power analysis performed in G\*Power 3.1.9.7 (Faul et al., 2007) with an expected effect size of 0.4, an alpha value of 0.05 and desired statistical power of 0.8. Inclusion criteria consisted of having no history of injury in the past three months and the ability to safely participate in exercise. These criteria were determined by the Nordic (Kuorinka et al., 1987) and Canadian Society of Exercise Physiology – Get Active questionnaires (<https://store.csep.ca/pages/getactivequestionnaire>) respectively. Individuals with prior occupational MMH experience were excluded from this study because their expertise may be a confounding factor (Scholz, 1993). Additionally, individuals who deemed themselves as experienced weightlifters, specifically with the squat, deadlift, or any other type of lifting exercise, were excluded. Finally, individuals who were allergic to adhesives were also excluded from the study for comfort and health reasons. Participants were asked to avoid performing highly strenuous exercise for three days prior to participation.

#### 4.2 Experimental Design

A repeated measures experimental design was used to address the research question. There were two separate collection sessions with at least 48-hours in between. Each session required participants to complete four bouts of lifting where within each session all four bouts were performed under one of two MMH task conditions. Exposure task conditions were randomized across participants (Figure 7). The two exposure conditions were: high-load low-frequency (HLLF) and low-load high-frequency (LLHF). “High” and “low” load were defined as 15% and 5% of participants’ lifting capacity, measured as their maximum voluntary isometric exertion in a semi-squat posture (Dolan & Adams, 1998). Each bout consisted of 7-minutes of repetitive lifting. Assuming that each lift lasts approximately 2 seconds, the associated lift

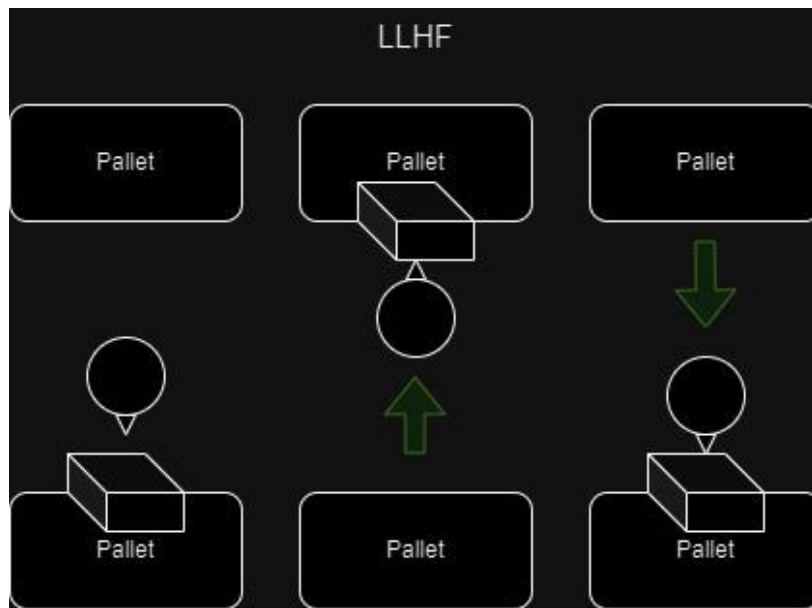
frequencies were set to 4 lifts per minute for the low frequency condition, and 12 lifts per minute for the high frequency condition. The prescribed load and frequency were held the same for all four lifting bouts within a session. This configuration ensured that the total external work done was the same between the HLLF and LLHF conditions (assuming similar lift and transfer paths). Within each lifting session, the four 7-minute bouts of lifting required the use of a: self-selected (SS<sub>1</sub>) strategy, stoop (ST) technique, squat (SQ) technique (where the stoop and squat forced participants to experience a range of biomechanical and metabolic sensations associated with the different techniques), and a repeat of the self-selected (SS<sub>2</sub>) strategy following the ST and SQ exploratory trials.



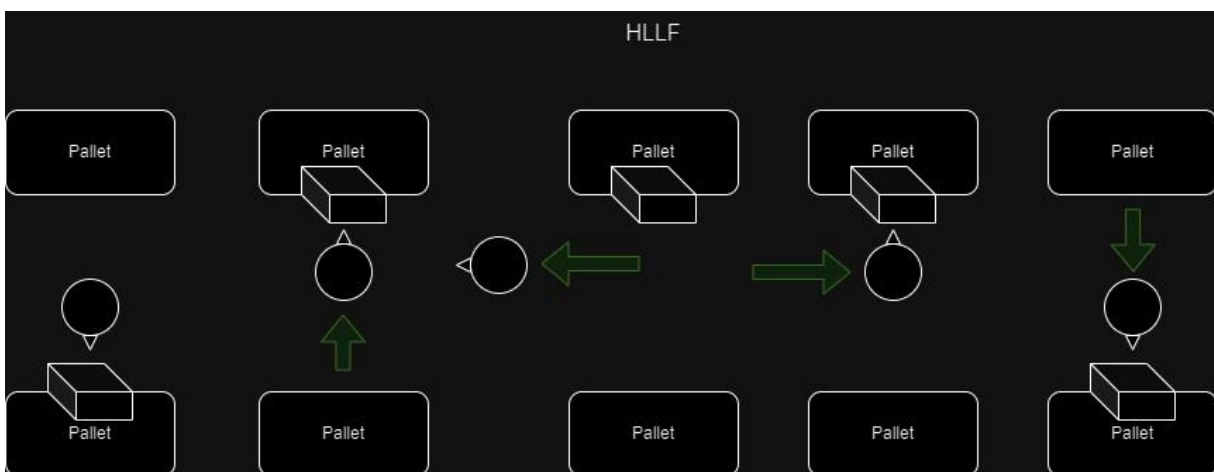
**Figure 7:** Flow chart illustrating the order of lifting technique conditions for each exposure condition series.

When lifting, participants were asked to synchronize their lifts to an audible metronome set at the prescribed frequency. Each bout consisted of repetitively lifting and transferring a weighted milk crate (loaded with the prescribed weight via dumbbell weights) between two pallets (Figure 8). The pallets were placed parallel to one another at a distance determined by the participant through two self-selected step lengths. In the HLLF condition, participants were also cued through the metronome to walk 2 step lengths out to the side between each lift to account

for the step-count difference between the exposure conditions (Figure 9). Although Selinger et al., (2015) and Selinger et al., (2019) found that 15-minute trial durations provided adequate time for participants to optimize their movement strategies in the context of gait, in the context of lifting 15-minutes of repetitive lifting may lead to undue fatigue for our untrained sample. Pilot testing revealed that 7-minutes was a suitable balance between providing the participants enough time to sample the new “cost landscape” while hopefully avoiding any confounding factors such as muscle fatigue. During piloting it was also noted participants would most likely reach steady state after 3-4 minutes of lifting.



**Figure 8.** *Birds eye view of the LLHF experimental setup*



**Figure 9.** *Birds eye view of the HLLF experimental setup*

### **4.3 Experimental Protocol**

On each day, participants completed one of two exposure conditions. Participants were not given instructions about how to lift during the SS trials but were given instruction to use specific techniques during the exploration phase which included bouts of lifting with squat and stoop techniques. Instructions on how to perform SQ and ST lifts (Appendix A) were presented through example images and verbal instruction that will be consistent across all participants. The ST and SQ trials can be thought of as “exploratory” trials with the purpose of encouraging participants to explore different movement-to-outcome relationships.

#### **4.3.1 Day One**

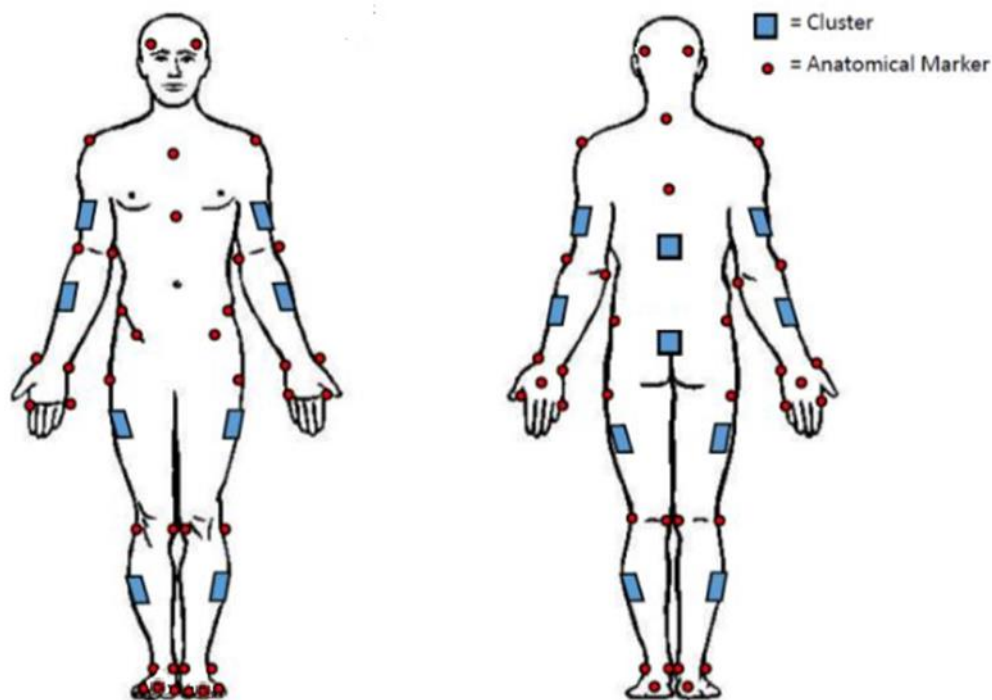
Once consented and included into the study, participants began with two maximum voluntary isometric exertions (MVEs) separated by a minimum 2 minutes of rest in a semi-squat posture to provide an estimate of max lifting capacity (as described in Dolan & Adams, 1998 and Fischer et al., 2015). The peak value from the two exertions was used as the maximum strength value. Following the MVEs, participants were first instrumented with a Polar H10 chest-strap mounted heart rate monitor, then an 86 passive-reflective whole-body marker set (Figure 10), and finally the VO2 Master which was calibrated per manufacturer instructions (Figure 11). After the markers were affixed, participants were asked to first perform a static standing “motor bike pose” calibration trial, then a dynamic calibration trial. The motor bike pose consisted of standing with the shoulders abducted to 90° and elbows flexed to 90° for approximately one second. The dynamic calibration trial consisted of three body-weight squats facing the first pallet followed by three body-weight squats facing the second pallet. These trials were required for data post-processing and modelling (Section 4.5 and 4.6.4).

After instrumentation was applied, heart rate after 10 seconds of quiet standing, and ratings of perceived exertion (RPE) on a 15-point (6-20) Borg RPE scale were recorded (Borg, 1990). These values were considered as the participant’s “resting” heart rate and resting RPE for the purpose of gauging rest in this protocol. Next, participants were asked to begin the first bout of lifting specific to the condition (i.e., HLLF or LLHF) that was randomly assigned for day one (Figure 7). Between-bout rest was a minimum of 10 minutes and participants were allowed to be

seated. Participants could begin the next trial if their heart rate had returned to within ten beats per minute of their “resting” heart rate and if they report that their RPE had returned to their ‘resting’ value. Overall, no participant required more than 10-minutes of rest to return to their “resting” heart rate and RPE values.

#### 4.3.2 Day Two

To ensure continued participant safety and study eligibility, participants were asked upon arrival at the lab if any aspect of their health status pertinent to the questionnaires from day one had changed. Participants repeated the MVIE protocol, and the mass was scaled to the new maximum strength value. They were then instrumented and asked to perform motion capture calibration trials similarly to day one. After being instrumented, participants completed the second exposure condition.



**Figure 10:** Cluster and marker instrumentation. Figure adapted from Remedios, Armstrong, Graham & Fischer, 2020.



**Figure 11:** *VO2 Master affixed to participant using a Hans Rudolph face mask. Figure retrieved from the VO2 Master Product Manual.*

#### **4.4 Data Collection and Instrumentation**

Motion capture data were recorded to capture the first 10, and last 10 lifts in each condition. Within the LLHF condition, this required three 1-minute collections at the beginning and end of each lifting bout. Within the HLLF condition, this involved twenty separate 7-second collections at the beginning and end of each lifting bout. Respiratory gas flow data was recorded throughout the entirety of each trial.

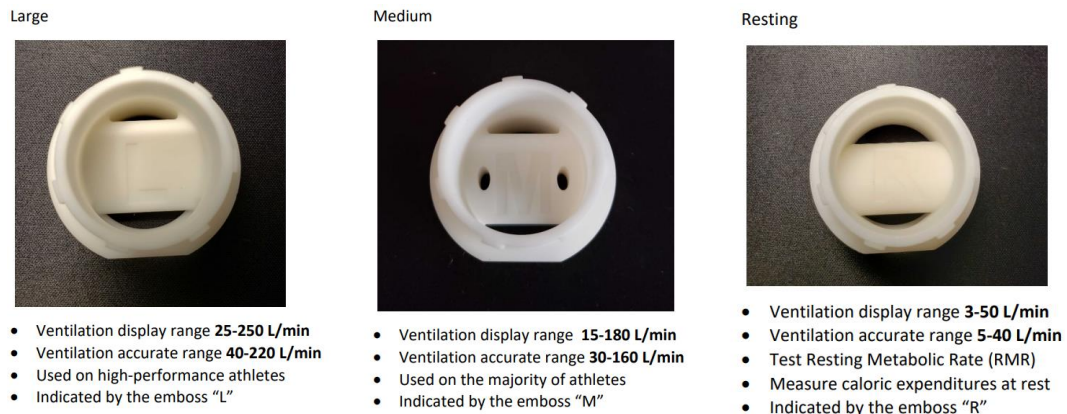
##### **4.4.1 Optical Motion Capture**

A 12-camera Vicon optical motion capture system was used (Vicon, Oxford, UK). Motion capture data was collected at a sampling frequency of 60Hz. The marker set (Figure 10) included 10 rigid marker clusters affixed to each of the following body segments: Feet, shanks, thighs, pelvis, trunk, upper arms and forearms. The marker set also included 46 individual markers on the following anatomical landmarks: acromions, lateral epicondyles, medial epicondyles, radial styloid processes, ulnar styloid processes, the base of the first, third and fifth metacarpals, iliac crests, anterior superior iliac spines, greater trochanters, lateral femoral condyles, medial femoral condyles, lateral malleoli, medial malleoli, base of the first and 5<sup>th</sup> metatarsals, anterior dorsal tarsal midline points, calcanei, 7<sup>th</sup> cervical vertebra, suprasternal notch, xiphoid process, 7<sup>th</sup> thoracic vertebra and the anterior and posterior lateral aspects of the head (Figure 10). Anatomical marker locations enabled local coordinate systems for each body segment to be defined in accordance with ISB standards (Wu et al., 2002, Wu et al., 2005). During collection

trials, all required markers and marker clusters remained on the participants to track the movement of each segment during dynamic motion. A total of 12 calibration markers were removed: bilateral acromion, T7, C7, suprasternal notch, xiphoid process, bilateral greater trochanter, bilateral anterior superior iliac spine, bilateral iliac crest.

#### 4.4.2 Gas Flow Analysis System

To calculate metabolic cost, ventilation and oxygen consumption was collected with a VO2 Master wearable metabolic system. Based on pilot testing of both lifting tasks (HLLF and LLHF) the ‘Medium’ user-piece was chosen for this study. Prior to each collection, the VO2 Master underwent a gas and flow calibration using the provided 3L Calibration Syringe (VO2 Master, 2022). No collection was performed unless the calibration registered as “Good”. Each 7-minute lifting bout was collected separately and exported into Excel files that contained one-second averages of ventilation, absolute  $\text{VO}_2$ , and heart rate data.



**Figure 12:** Available user-pieces and specifications as described by the manufacturer. Figure retrieved from the VO2 Master Product Manual.

#### 4.5 Data Conditioning and Modelling

With the collected kinematic data, subsequent data processing and conditioning was completed to build a biomechanical model and calculate biomechanical outcome metrics using a top-down inverse dynamics approach.

#### **4.5.1. Labelling and Gap-filling 3D Motion Capture Data**

All motion capture data were processed in Vicon Nexus 2.6.1 (Vicon, Oxford, UK). Raw marker data for each participant were constructed and labelled. Each reconstructed trial was visually analyzed frame-by-frame to ensure that trajectories were properly labeled and free of any significant gaps or mislabels. If gaps were present, ‘rigid body fill’ was used first, which fills in marker gaps based on the unchanging distance between the missing marker and the three other markers on the same segment. If ‘rigid body fill’ was not possible, ‘pattern’ fill was used which fills in the marker gaps based on the assumed unchanging distance between the missing marker and one other marker on the same segment. The last option used to gap fill was ‘spline fill’, which was only used for gaps smaller than 10 frames (Howarth and Callaghan, 2010). Once the static calibration trial was properly labelled and gap-filled, a calibration pipeline was used to streamline the labelling of the dynamic calibration trial. Similarly, the dynamic calibration trial was assessed frame-by-frame for labelling and gaps. Finally, the labelling pipeline was used to automate the labelling of the rest of the lifting trials.

#### **4.5.2. Modelling with Visual3D**

Once labelled and gap-filled, the marker data were imported into Visual3D (V3D) (C-Motion, Germantown, Maryland). A dual-pass, low-pass 4<sup>th</sup> order Butterworth filter with an effective cut-off frequency of 6 Hz (Winter, 1990) was applied to the marker position data in V3D. Using the static calibration trial, a skeleton model and landmarks were created for each participant, with the corresponding landmark orientations set. Then, the segments were created by defining the proximal and distal joints (and the corresponding radii). For segment masses, the Dempster’s regression equations (Dempster, 1955) were used (default setting within Visual3D). The moment of inertia of a segment as well as the centre of mass locations were set as per Hanavan’s mathematical model (Hanavan, 1964). In terms of segment geometry, the trunk and pelvis were cylindrical, while the limbs were all conical. The model created used the segment definitions and joint locations described in Table 2.

Inverse kinematic constraints were applied to the rigid link segment models to restrict degrees of freedom (DOF) between segments based on how joints move (through default settings: algorithm for computing pose is Visual3D 6DOF, optimization algorithm is Levenberg

Marquardt). For all lifts, a top-down modelling approach was used since participants did not reliably perform each lift on a force-plate.

For each participant, once the skeleton model was created using the static calibration trial, it was applied to each dynamic lift captured. The visual representation of the model was used to review and ensure that all prior Vicon marker labelling was correct. If any errors (e.g., mislabelled markers) were detected, corrections were made in Vicon before proceeding forward with any processing in Visual3D.

Once all lifts were assessed to be correctly labelled, the mass of each hand was increased by half of the known box mass. This method of modelling the interaction between the load and the hands improves upon past methods that apply a gravity-oriented static half-load to each hand by considering the acceleration of the load (Akhavanfar et al., 2021).

**Table 2.** *Segment definitions – Identifying the distal/proximal segment points and calculation of joint center locations*

Segment	Definition
Torso	Distal joint center: mid-point between the left and right acromion markers Proximal joint center: mid-point between the left and right iliac crest markers Depth of torso: distance between the suprasternal notch and C7 markers
Upper arm	Proximal joint center/shoulder joint center: <ul style="list-style-type: none"> <li>- Starting point: acromion</li> <li>- End point: mid-point between left and right acromion markers</li> <li>- Lateral object: mid-point between the left and right iliac crest markers</li> <li>- Offset in axial direction by 0.05%</li> <li>- Radius: midpoint between lateral and medial epicondyles</li> </ul> Distal joint center/elbow joint center: midpoint between lateral and medial epicondyles <ul style="list-style-type: none"> <li>- Radius: midpoint between L_EPI and M_EPI</li> </ul>
Forearm	Proximal joint center: elbow joint center  Distal joint center/wrist joint center: midpoint between ulnar styloid marker and radial styloid marker <ul style="list-style-type: none"> <li>- Radius: midpoint between L_EPI and M_EPI</li> </ul>

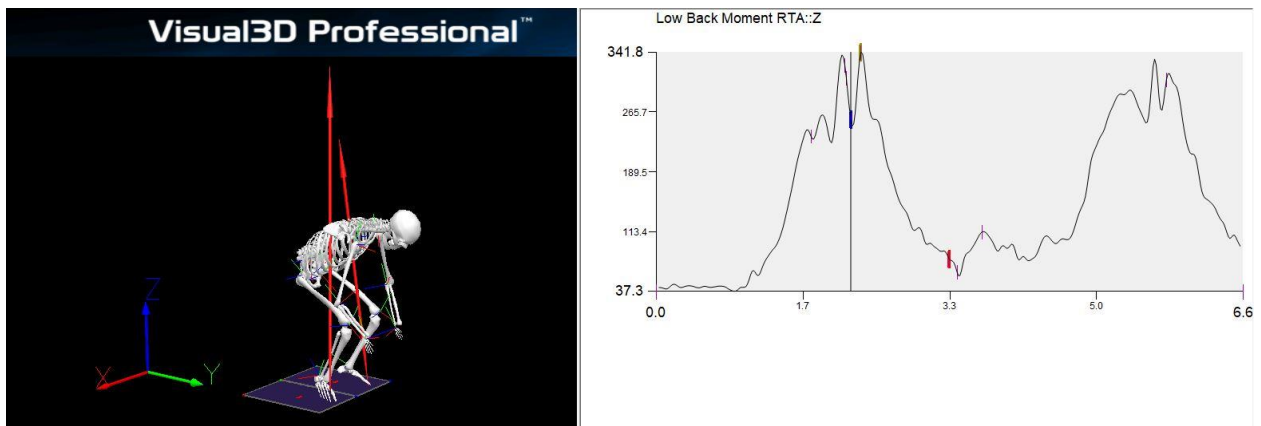
Hands	Proximal joint center/wrist joint center <ul style="list-style-type: none"> <li>- Distal lateral landmark: H1</li> <li>- Distal medial landmark: H2</li> </ul> Tracking targets: H1, H2, H3
Pelvis	Pelvis Segment type: Coda pelvis (Coda Pelvis, 2019) <ul style="list-style-type: none"> <li>- Defined using anatomical location of the ASIS and PSIS (ASIS and PSIS used as reference points of defining pelvis coordinate system)</li> </ul> Proximal/Origin point <ul style="list-style-type: none"> <li>- Mid-point between ASIS markers</li> </ul> Distal point <ul style="list-style-type: none"> <li>- Mid-point between P1 and P4 marker on the pelvis cluster (approximately where sacrum is located)</li> <li>- The Coda pelvis uses the midpoint between the PSIS to identify where the sacrum is located</li> </ul> Orientation <ul style="list-style-type: none"> <li>- X-Y plane: through R_ASIS and L_ASIS and mid-point of the R_P SIS and L_P SIS (in this case, we defined mid-point between PSIS as SACR)</li> <li>- x-axis: origin to R_ASIS</li> <li>- y-axis: perpendicular to X-Y plane</li> <li>- z-axis: cross product of z-axis and x-axis</li> </ul>

*Note.* ‘L\_EPI and R\_EPI’ – left and right epicondyles, ‘H1, H2, H3’ – hand markers, ‘L\_ASIS and R\_ASIS’ – left and right anterior superior iliac spine, ‘L\_P SIS and R\_P SIS’ – left and right posterior superior iliac spine, ‘SACR’ – sacrum.

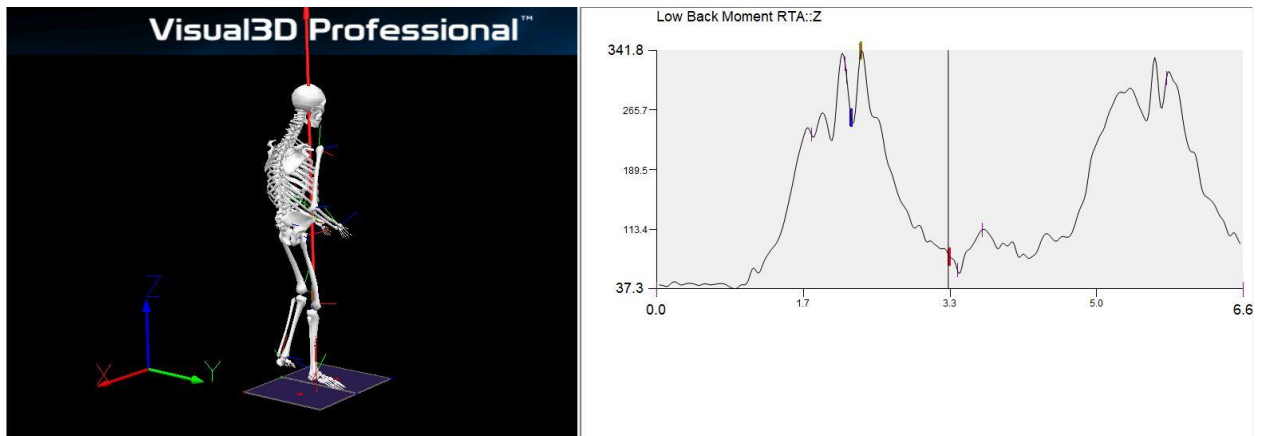
### 4.5.3. Identifying Events

The start and end of each lift were defined in a manner that was consistent across all participants. To precisely identify the start and end events, within Visual 3D, a pipeline was created to detect changes in the position and velocity signals of the distal forearm. First, several events were created to systematically identify key-points in the lifting trials. An event at the first global minimum of the distal-end position of the forearm in the vertical direction (Z-axis) was created as the lowest point reached by the hands when reaching and grasping the milk crate. The minimum and maximum distal-end position of the forearm in the anterior-posterior direction (Y-

axis) was created as the positions reached at each pallet. An event was created when the distal-end position of the forearm crossed the midpoint between the two pallets to signal that the participant had committed to transferring the milk crate. The event at the grasping of the milk crate and the transfer between the two pallets were used as boundaries to find the start and end of the lifts. The start of the lift was defined as the moment when the distal-end velocity of the forearm exceeded 0.1 m/s on ascent (Figure 13). The end of the lift was defined as the subsequent moment when the distal-end velocity of the forearm reached 0.1 m/s on descent (Figure 14).



**Figure 13:** *The start of the lift identified through Visual3D threshold event detection*



**Figure 14.** *The end of the lift identified through Visual3D threshold event detection*

## 4.6. Calculation of Biomechanical and Metabolic Outcome Measures

The following measures were selected as biomechanical and metabolic outcome measures to determine whether an exploration period could play a role in reducing exposure metrics between self-selected lifting bouts.

### 4.6.1. Peak L4/L5 Sagittal Plane Moments

Time-series sagittal L4/L5 moments were calculated in Visual3D. A top-down approach was used to calculate joint moments about the distal torso ‘joint’, which was defined as the sacrum relative to the torso segment. Therefore, the joint moments were resolved within the torso coordinate system. To find the peak low back moment, a global maximum event was defined between the start and end of the lift events in the sagittal low back moment signal. The metric signal value at this event was then found and exported for each lift. Finally, the peak low back moments for the first and last 10 lifts of each lifting technique were averaged within each participant.

### 4.6.2. Lift Duration

The lift duration was calculated as a secondary measure to further explain any findings related to our primary outcome variables. To calculate the duration of each lift, the time between the start and end of each lift was generated in Visual3D and then exported. The lift durations were then averaged within participant.

### 4.6.3. Squat-Stoop Index

The Squat-Stoop Index (SqStI) developed by Schmid (2022) was calculated as another secondary measure to quantify the different lifting postures achieved. The following equation was used to calculate the SqStI at the start of each lift in Visual3D.

$$StSq = 100 - \left( \frac{(Vert\_HJC_{Standing} - Vert\_HJC_{Bending}) * 100}{Vert\_C7_{Standing} - Vert\_C7_{Bending}} \right)$$

The vertical position of the C7 spinous process was derived directly from the marker placed over the C7 spinous process and tracked using four head markers during motion trials. The vertical position of the hip joint center was approximated in Visual3D. The SqStI for the first and last 10 lifts of each lifting technique were averaged within each participant.

#### **4.6.4. Metabolic Cost**

Once exported from the VO2 Master app, absolute VO<sub>2</sub> was normalized for each lifting bout. The average relative VO<sub>2</sub> consumption in ml.kg.min was then calculated for each minute of lifting using a custom Python script. The average relative VO<sub>2</sub> consumption for the last 3-minutes of each lifting technique was averaged within participants as an indicator of metabolic cost. The average ventilation for the last 3-minutes of lifting for each participant was also averaged across each task condition.

#### **4.7. Hypothesis Testing**

The dependent variables required to test the stated hypothesis included: the mean of the peak sagittal L4/L5 moment (Section 4.6) from each of the last 10 lifts within the SS<sub>1</sub> technique lifting bout, and within the last 10 lifts of the SS<sub>2</sub> technique bout. The mean relative VO<sub>2</sub> consumption over the last 3 minutes of the SS<sub>1</sub> and SS<sub>2</sub> trials were also retained as dependent variables.

Two-way repeated measures ANOVAs with an alpha value of 0.05 were performed to compare biomechanical and metabolic dependent variables between task conditions (HLLF and LLHF) and across technique (SS<sub>1</sub> and SS<sub>2</sub>). Where significant interaction effects were observed post-hoc testing was conducted with the level of significance adjusted with a Bonferroni correction. Statistically significant differences between SS trials were interpreted as evidence that participants may have adapted their lifting strategy to control for the respective performance criteria variable after an exploratory phase. Therefore, the detection of statistically significant differences in biomechanical and metabolic dependent measures between SS trials where SS<sub>2</sub> < SS<sub>1</sub> in HLLF and LLHF respectively, would support our hypothesis.

# Chapter 5

## Results

### 5.1. Demographics

Participant demographics are detailed in Table 3, and between-day MVICs are reported in Table 4 without participant code to respect participant confidentiality. The MVIC of participants varied between days by at most 5%. The relative max lifting capacity also varied between participants, and the average load lifted in each task condition can also be found in Table 3.

**Table 3.** *Participant demographics and average load lifted in each task condition.*

Participants	n	26
Sex	F	n = 15
	M	n = 11
	Mean	SD ( $\pm$ )
Age (years)	25.6	7.3
Height (m)	1.77	0.09
Mass (kg)	70.92	12.22
HLLF load (kg)	13.7	4.75
LLHF load (kg)	4.56	1.5

**Table 4.** *Recorded MVICs between task condition days and their respective percent differences.*

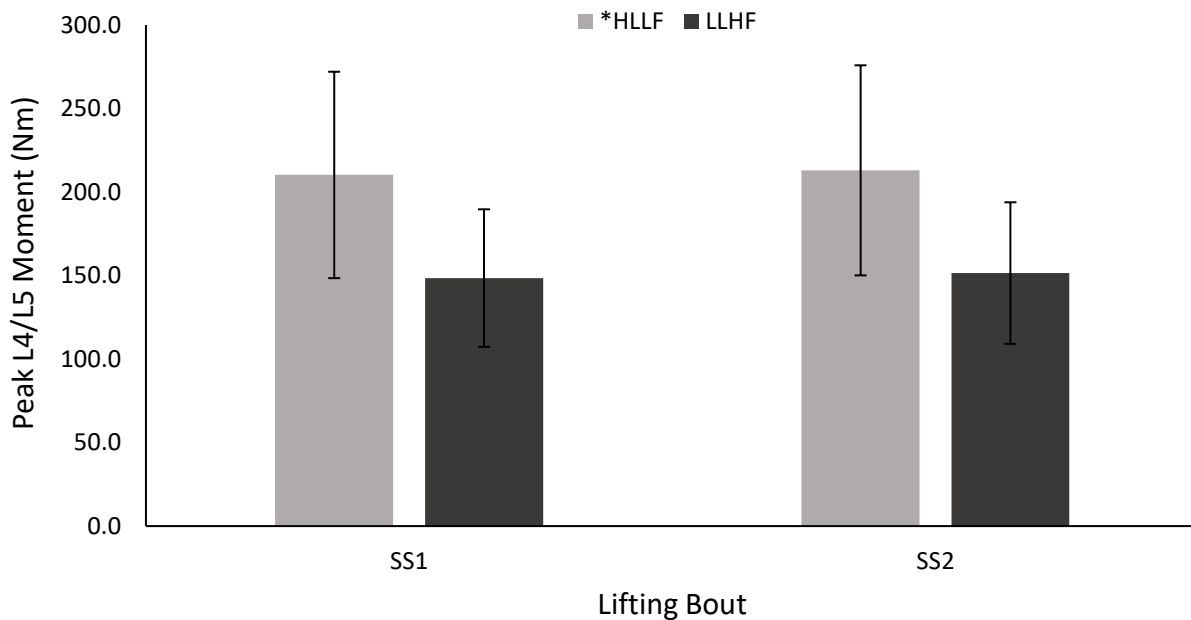
MVIC (N)		Difference (%)
HLLF	LLHF	
592	606	1.6
1027	1075	3.0
991	1006	1.0
806	831	2.0
1109	1066	2.7
671	641	3.1
1354	1288	3.4
1277	1250	1.4
1456	1395	2.9
1229	1204	1.4
703	748	4.1
479	445	5.0
799	830	2.5
681	719	3.6
879	915	2.7
683	647	3.6

633	636	0.3
631	635	0.4
730	684	4.4
1246	1196	2.7
555	572	2.0
1356	1402	2.2
712	729	1.6
781	770	0.9
745	731	1.3
1537	1551	0.6

## 5.2. Hypothesis Testing

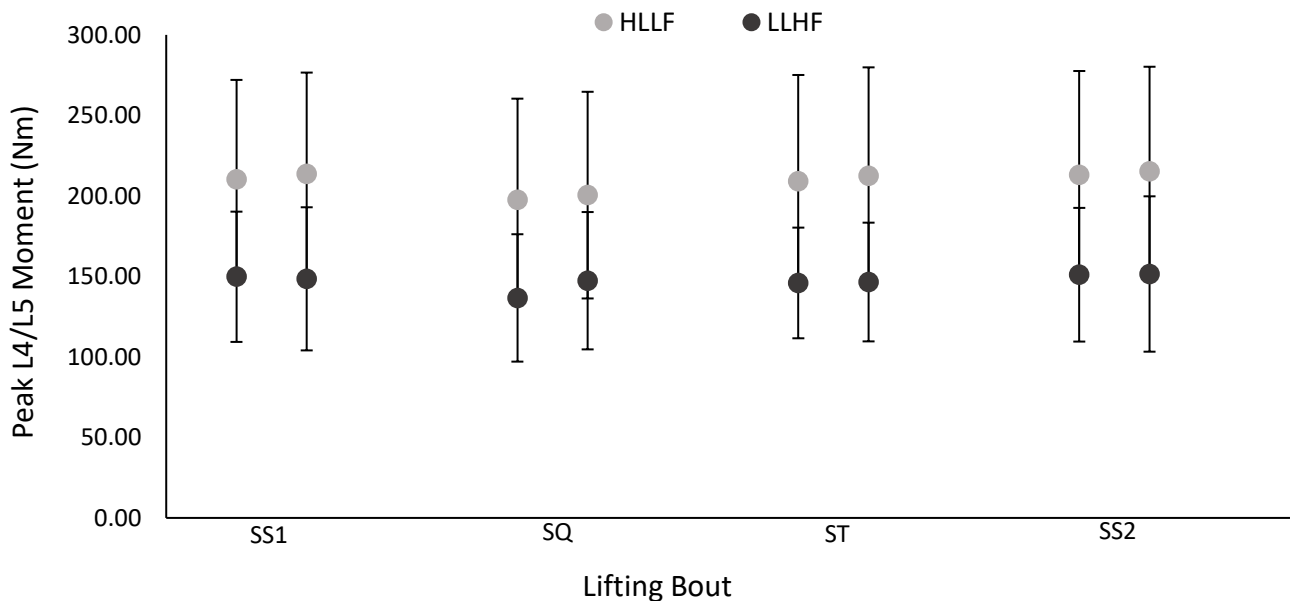
### 5.2.1. Peak Sagittal L4/L5 Moment

For the mean peak sagittal L4/L5 moments (Nm) a significant main effect for task was found ( $F = 91.89$ ;  $p < 0.001$ ), but no main effect of time ( $F = 1.22$  ;  $p = 0.28$ ) or interaction ( $F = 0.46$  ;  $p = 0.50$ ) was found. The HLLF condition resulted in significantly greater peak sagittal L4/L5 moments ( $64.6 \pm 6.74$  Nm;  $p < 0.001$ ) (Figure 15).



**Figure 15.** Comparison of the mean peak sagittal L4/L5 moments (Nm) between the SS<sub>1</sub> and SS<sub>2</sub> lifting bouts for both task conditions (last ten lifts). A 2-way *rmANOVA* revealed that the HLLF condition had significantly greater peak L4/L5 moments. \*  $p < 0.05$

Once averaged across each participant, group mean peak sagittal L4/L5 moments for all techniques varied around  $211 \pm 7\text{Nm}$  in the HLLF condition, and  $149 \pm 2\text{ Nm}$  in the LLHF condition. Within the last ten lifts, the greatest difference in mean peak sagittal L5/L5 moment was 14.7 Nm between the SS<sub>2</sub> and SQ lifting bouts in the HLLF condition, and 6.0 Nm between the SS<sub>1</sub> and SS<sub>2</sub> lifting bouts in the LLHF condition. Figure 16 visually highlights the significant difference between each task condition (HLLF vs LLHF), and the minimal differences between the SS<sub>1</sub> and SS<sub>2</sub> lifting bouts within each task conditions.

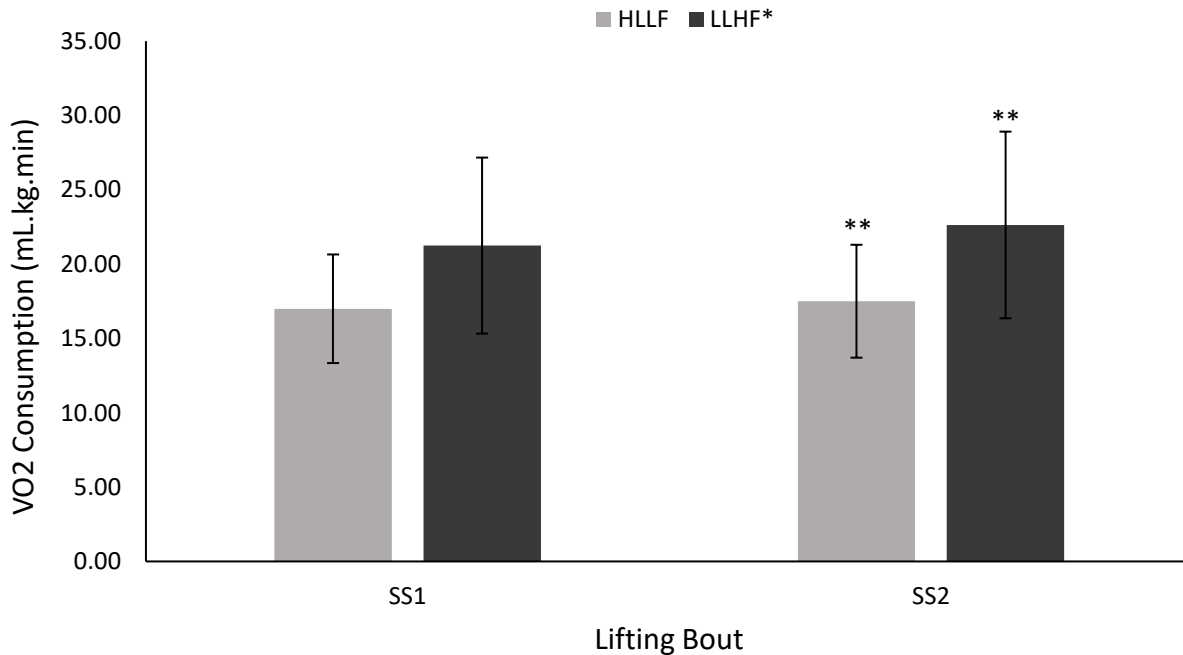


**Figure 16.** Mean peak sagittal L4/L5 moments (Nm) for the first and last ten lifts averaged across all participants for both task conditions.

### 5.2.2. Relative VO<sub>2</sub> Consumption

For the mean VO<sub>2</sub> consumption (mL.kg.min) a significant main effect for task ( $F = 30.06$ ;  $p < 0.001$ ), and time ( $F = 5.54$ ;  $p < 0.05$ ) were found, but no interaction effect ( $F = 2.81$ ;  $p = 0.10$ ) was found. The LLHF condition resulted in significantly greater VO<sub>2</sub> consumption ( $4.69 \pm 0.86\text{ mL.kg.min}$ ;  $p < 0.001$ ) compared to the HLLF condition, and the SS<sub>2</sub> technique had significantly greater VO<sub>2</sub> consumption ( $0.95 \pm 0.403\text{ mL.kg.min}$ ;  $p < 0.05$ ) compared to the SS<sub>1</sub>

technique (Figure 17). When averaged across the last three-minutes of lifting, mean VO<sub>2</sub> consumption (mL.kg.min) for both task conditions followed a similar trend where SQ (HLLF: 18.95 ± 3.80 mL.kg.min / LLHF: 26.99 ± 6.28 mL.kg.min) yielded the greatest VO<sub>2</sub> consumption and ST (HLLF: 15.87 ± 3.05 mL.kg.min / LLHF: 20.61 ± 5.06 mL.kg.min) yielded the least VO<sub>2</sub> consumption.



**Figure 17.** Comparison of the mean VO<sub>2</sub> consumption (mL.kg.min) between the SS<sub>1</sub> and SS<sub>2</sub> techniques for the last three-minutes of lifting. A 2-way rmANOVA revealed a main effect of task (LLHF > HLLF) and a main effect of time (SS<sub>2</sub> > SS<sub>1</sub>). Task condition \* p<0.05 ; Time condition \*\* p<0.05

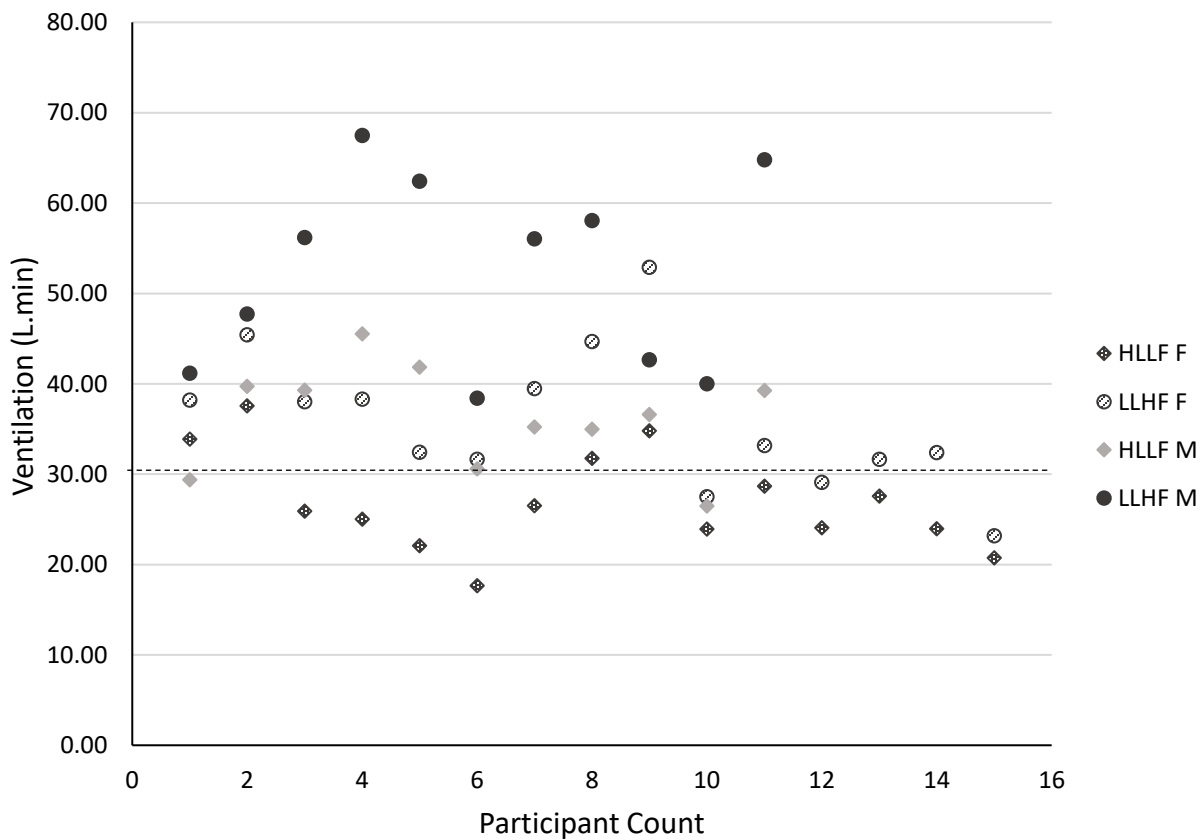
### 5.3. Secondary Analysis

Noting that the results did not support the hypothesis, a set of secondary analyses were performed to explain the novel findings.

#### 5.3.1. Ventilation

Since each mouthpiece assumes a ventilation range and the medium mouthpiece was used in this study, a secondary analysis was completed to verify the frequency of ventilations occurring within the primary range of the medium mouthpiece. The mean ventilation for the last

three-minutes of lifting averaged across all techniques for each participant varied from as low as 17.6 L.min in the HLLF condition, to as high as 67.5 L.min in the LLHF condition. The HLLF condition contained 13/26 instances where the mean ventilation for the last three-minutes of lifting was lower than 30 L.min, the minimum suggested ventilation for the medium mouthpiece, 11 of which were from female participants, and 2 of which were from male participants (Figure 17). In comparison, the LLHF condition contained 3/26 instances where the mean ventilation was lower than 30 L.min, all of which were from female participants (Figure 19).

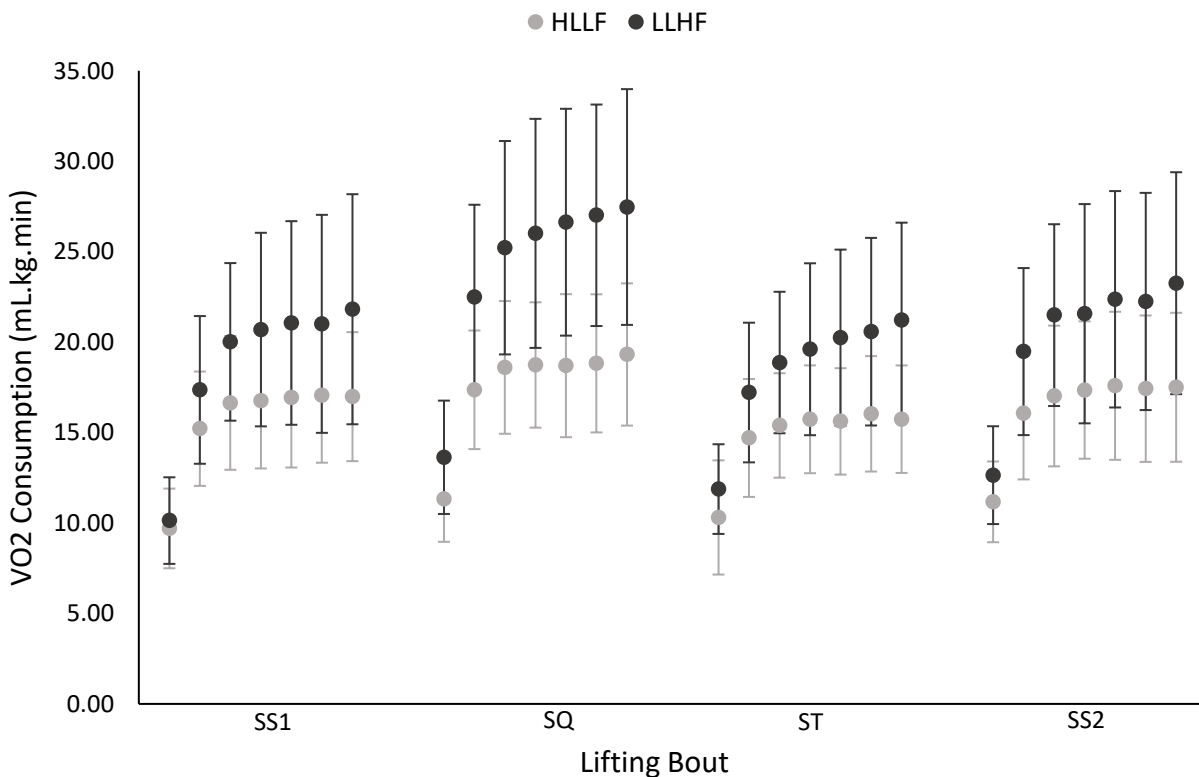


**Figure 18.** *The mean ventilation for the last 3-minutes of lifting condition for each participant in relation to the recommended 30 L.min use-range for the VO2 Master medium user-piece.*

### 5.3.2. Changes within Lifting Bouts

To better understand how the biomechanical and metabolic exposures of participants may have changed within the course of each lifting bout, a secondary analysis was performed to investigate whether significant differences existed between the beginning and end of each lifting bout. The mean peak sagittal L4/L5 moments for the first ten lifts of each lifting bout were quantified and no statistically significant differences were found across lifting bouts between the first and last ten lifts in the HLLF ( $F = 4.04$  ;  $p = 0.055$ ) or LLHF ( $F = 0.048$  ;  $p = 0.83$ ) conditions.

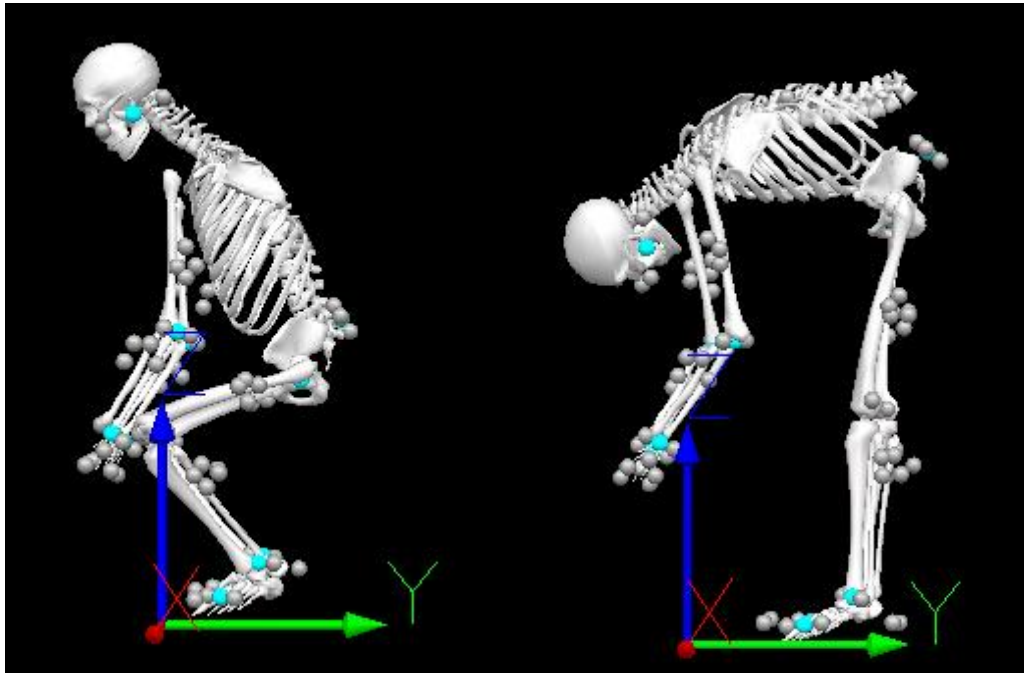
The relative  $VO_2$  consumption was averaged across every minute of each lifting bout. Visually, Figure 18 shows how in the HLLF condition, the relative  $VO_2$  consumption of participants typically reached a steady state after 2-3 minutes of lifting, but in the LLHF condition, participants seemed to have still been trending upwards after 3-4 minutes of lifting.



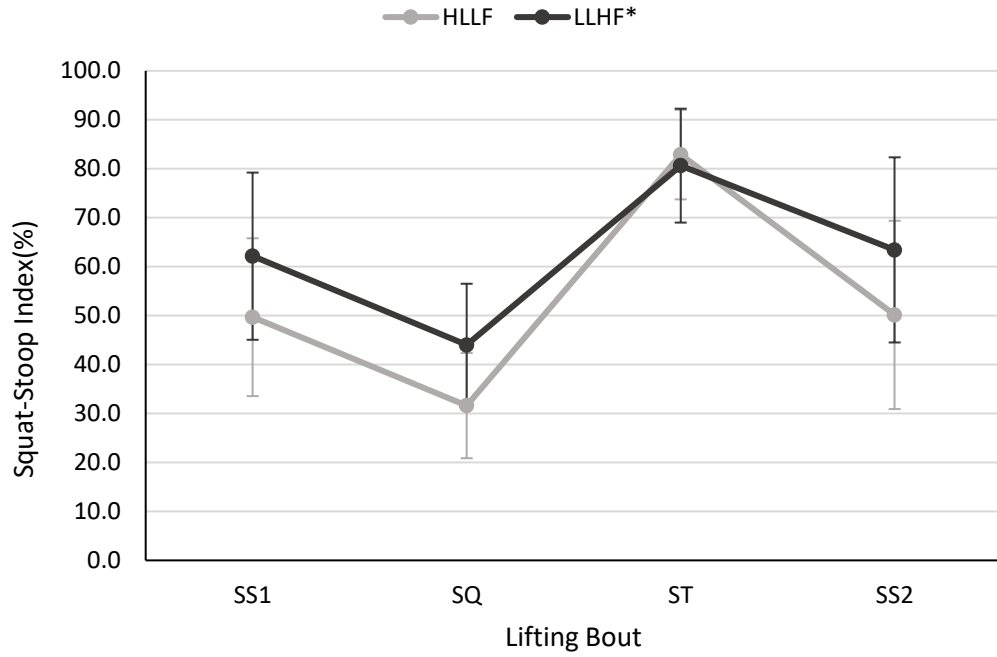
**Figure 19.** Mean  $VO_2$  consumption (mL.kg.min) for each minute of lifting within each lifting bout averaged across all participants.

### 5.3.3. Squat-Stoop Index

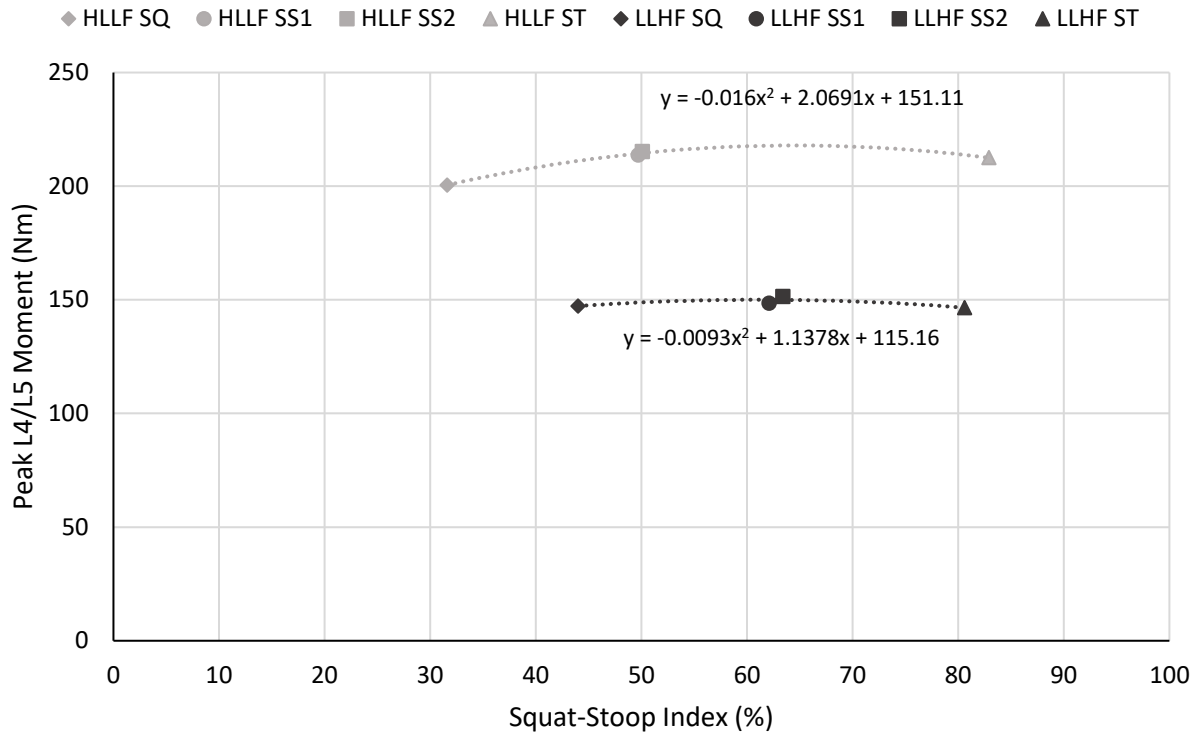
To quantify changes in lifting movement strategy independent of the biomechanical and metabolic outcomes, the Squat-Stoop Index (SqStI) was calculated for each lift (Figure 21). For the group mean SqStI for the last ten lifts a significant main effect for task was found ( $F = 20.01$ ;  $p < 0.001$ ), but no main effect of time ( $F = 0.16$  ;  $p = 0.69$ ) or interaction ( $F = 0.07$  ;  $p = 0.80$ ) was found. The group mean SqStI for the last ten lifts was greater in the LLHF condition by on average 13% (i.e. closer to a stoop lift). The SqStI ranged from  $31.6 \pm 10.7$  % (SQ) to  $82.9 \pm 9.1$  % (ST) for the HLLF condition, and  $44.0 \pm 12.5$  % (SQ) to  $80.6 \pm 11.6$  % (ST) for the LLHF condition. However, the change in SqStI between the SS<sub>1</sub> and SS<sub>2</sub> lifting techniques was 0.4 % within the HLLF condition, and 1.3 % within the LLHF condition (Figure 22). Using the mean SqStI of the last ten lifts to plot peak L4/L5 moment and VO<sub>2</sub> consumption, we see a relationship of increased VO<sub>2</sub> consumption with a lower SqStI (i.e. closer to a squat lift), and a relatively unaffected peak L4/L5 moment with varying SqStI values (Figure 23, Figure 24).



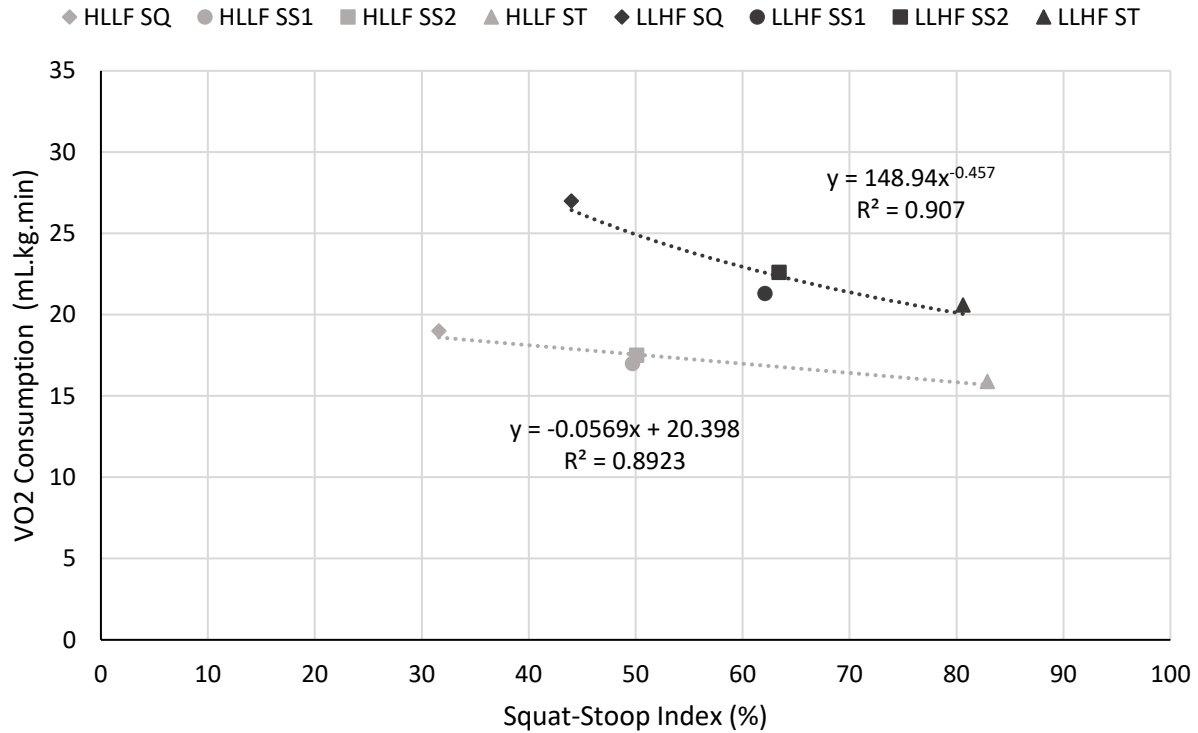
**Figure 20.** *The lifting postures corresponding to a Squat-Stoop Index of 14.7 (left) and 96.1 (right).*



**Figure 21.** *The mean Squat-Stoop Index for the last ten lifts averaged across all participants for each task condition. A 2-way rmANOVA revealed that the LLHF condition had significantly greater SqStI values. \*  $p < 0.05$*



**Figure 22.** The mean peak L4/L5 moment for the last ten lifts for both task conditions plotted against the mean SqStI of the last ten lifts. A 2<sup>nd</sup> order polynomial function was fit to both sets of data.



**Figure 23.** The mean  $VO_2$  consumption for the last three-minutes of both task conditions plotted against the mean SqStI of the last ten lifts. A power function was fit to the LLHF data, and a linear function was fit to the HLLF data.

### 5.3.4. Lift Duration

Since lifting speed / lift duration have been previously observed as potential variables of interest in occupational lifting, a secondary analysis was performed to quantify the duration of each lift to reveal any potential changes due to the task condition or lifting bout. The range of lift durations for the last ten lifts varied, with the longest lift duration being 1.32s for SS<sub>2</sub> in HLLF, and the shortest lift duration being 0.95s for SS<sub>2</sub> in LLHF. On average LLHF lifting durations (~0.80s) trended lower than HLLF lifting durations (~0.98s), but statistical analysis was not completed (Table 5).

**Table 5.** *The means, standard deviations (SD) and ranges for the lift duration (s) of the last 10 lifts of each lifting bout.*

HLLF					LLHF				
Technique	Mean	SD (±)	Range		Technique	Mean	SD (±)	Range	
			Low	High				Low	High
SS <sub>1</sub>	0.99	0.12	0.79	1.35	SS <sub>1</sub>	0.84	0.09	0.71	0.96
SQ	0.95	0.11	0.71	1.17	SQ	0.80	0.09	0.70	1.01
ST	1.02	0.14	0.77	1.24	ST	0.84	0.08	0.65	1.03
SS <sub>2</sub>	0.96	0.11	0.80	1.32	SS <sub>2</sub>	0.82	0.09	0.69	0.95

## Chapter 6

### Discussion

The overarching purpose of this study was to investigate the biomechanical and metabolic determinants of occupational lifting movement strategy by leveraging a similar movement exploration paradigm in the optimal control of gait. Stemming from the theoretical principles of OFC theory, we believed that individuals would select different movement strategies, and adapt once provided relevant sensory feedback, to control for certain task relevant performance criteria. Therefore, we sought to test the hypothesis that untrained lifters would adapt their lifting movement strategy after an exploration period to minimize biomechanical exposure and metabolic cost in the HLLF and LLHF conditions respectively. The results of this study did not support the hypothesis that participants would adapt their movement strategies post-exploration; however, it does demonstrate how task parameters can influence the preferred lifting movement strategy and provides a novel attempt to understand movement strategy selection in a dynamic lifting context. Future work can build upon this study by utilizing the same research paradigm while controlling additional factors such as lifting expertise or functional capacity to further probe similar questions related to lifting movement strategy.

#### 6.1. Biomechanical Exposure

Though peak sagittal L4/L5 moments were indeed different between the HLLF and LLHF conditions, participants did not alter their peak sagittal L4/L5 moments following an exploration within either condition, contrary to the hypothesis. However, participants did adopt different lifting strategies between LLHF and HLLF conditions, exhibiting a more squat like posture in the HLLF condition and a more stoop-like posture in the LLHF condition.

The main effect of task on peak sagittal L4/L5 moments served as a proof of concept for our study design, where the HLLF condition was successful in being more demanding in terms of its 'biomechanical exposure'. Additionally, the main effect of task on the SqStI variable further demonstrates that movement behaviours are indeed dependent on the demand of the task. These data suggest that a more squat-like posture is likely when the load is heavier. Tying back to OFC theory, we believed that since the biomechanical exposure experienced in the HLLF condition would be significantly greater compared to the LLHF condition, we hypothesized that participants in the HLLF condition would adapt their movement strategy to minimize peak

sagittal L4/L5 moments once given relevant sensory feedback through exploring different lifting movement patterns. This wasn't the case, but this may be because a change in technique between stoop and squat did not sufficiently change peak sagittal L4/L5 moments (i.e., there wasn't enough change in the sensory stimulus to nudge the movement strategy towards a local minimum.

Multiple studies have looked at the differences in the biomechanical outcomes between squat, stoop, and semi-squat lifting techniques, and the results are mixed (Straker, 2003; van Dieën et al., 1999). The squat lift is widely regarded and recommended as the proper technique for lifting lower-lying objects because it is thought to produce lower mechanical stress on the lower back, but it is important to consider the possible types of mechanical stress. The squat lift has been found to be beneficial in terms of shear forces on the spine, but its potential positive effects in terms of net moments and compression forces were limited to a specific range of lifting tasks (van Dieën et al., 1999). The stoop technique is widely recommended against and considered the incorrect or 'lazy' way of lifting because it is thought to produce the opposite effect. However, in lifting tasks where the load is not lifted from a position between the feet, the net moment and compression on the spine tended to be lower using the stoop technique (van Dieën et al., 1999). In the context of this study, the squat and stoop lifting techniques were not considered as one being better than the other, but simply as two different movement patterns that can accomplish the same task of lifting while likely producing two sets of differing sensations/perceptions. However, results suggest that variations in technique within a condition did not sufficiently alter peak sagittal L4/L5 spine moments, which may explain why data did not support the specific hypothesis, though increased biomechanical exposure via altered load did nudge participants towards a more squat-like posture at lift initiation.

## **6.2. Metabolic Cost**

We anticipated that the relative  $\text{VO}_2$  consumption would be reduced following an exploration period, but only in the LLHF condition that was included to more acutely challenge the metabolic system. Higher relative  $\text{VO}_2$  in the LLHF condition compared to the HLLF condition served as proof that the LLHF condition was successful in being more acutely challenging on the metabolic system. However, contrary to the hypothesis, relative  $\text{VO}_2$  consumption increased following the exploration period and in both conditions, although lifting

strategy characterized as the SqStI remained stable pre-post exploration. We believe that the significant increase in  $VO_2$  from SS<sub>1</sub> to SS<sub>2</sub> is likely due to the cumulative effect of excess post-exercise oxygen consumption (EPOC), where oxygen uptake can be elevated above resting levels for some period of time post-exercise. The ‘rapid component’ of EPOC decays within approximately 1-hour, therefore the three ten-minute resting bouts nested within the lifting protocol were likely insufficient in suppressing the effects of EPOC (Børsheim & Bahr, 2003). The increase in  $VO_2$  due to the rapid component of EPOC is because of the associated underlying mechanisms such as the replenishment of oxygen stores in blood and muscle, lactate removal, and the resynthesis of creatine phosphate (Børsheim & Bahr, 2003). Therefore, since lifting strategy remained the same pre-post exploration, the significant increase in  $VO_2$  over time was likely not due to changes in lifting movement strategy, but due to the transient effect of EPOC.

Upon further examination of the one-minute averages for the relative  $VO_2$  consumption of all participants, it seemed that in the HLLF condition, participants achieved a steady-state after 3-minutes of repetitive lifting. However, relative  $VO_2$  consumption in the LLHF condition seemed to have still been trending upwards after 3-minutes of lifting (Figure 20). Differences between the third and last minute of lifting further revealed that participants may not have achieved a steady state in the LLHF condition (Table 6).

**Table 6.** *The mean change in relative  $VO_2$  consumption (mL.kg.min) from the third minute of lifting to the last minute of lifting.*

<u>Task</u>	<u>HLLF</u>	<u>LLHF</u>
SS <sub>1</sub>	0.34	1.80
SQ	0.72	2.25
ST	0.35	2.34
SS <sub>2</sub>	0.48	1.77
Mean	0.47	2.04

From previous work in the optimal control of gait, it was noted that it took three minutes for participants to reach steady-state step frequencies and net metabolic power (Selinger, 2015; Selinger, 2019). However, walking expends relatively low amounts of energy when compared to repetitive lifting. Previous studies examining the metabolic cost of lifting found similar relative  $VO_2$  consumption values within this study ranging from 15-30 mL.kg.min (Garg & Herrin, 1979;

Hagen et al., 1994; Welbergen et al., 1991). Therefore, although participants may not have reached a steady-state, their relative  $\text{VO}_2$  consumption did not exceed the expected range based on previous research.

In contrast to walking, due to the changes in trunk posture and positioning, lifting likely requires greater postural stabilization using the muscles of the abdominal wall. The increase in intra-abdominal pressure due to abdominal wall muscle activation has been theorized by some to increase lumbar spinal stability (Cholewicki et al., 1999). However, in addition to regulating intra-abdominal pressure, the muscles of the abdominal wall such as the diaphragm are also responsible for maintaining sufficient ventilation. A study done by Sembera et al., in 2023 showed that increased levels of abdominal bracing during lifting resulted in decreased total lung volume. Therefore, although this exceeds the scope of the current study, it is important to consider how the muscles of the abdominal wall may have affected the breathing and ventilation of participants during lifting compared to if they were walking.

Through the lens of OFC theory, we believed that participants would consider the increased metabolic cost due to the LLHF condition as a task relevant performance criterion and adapt their movement patterns accordingly. Although the underlying mechanisms behind how individuals may sense varying energy costs are not fully understood, the evidence that supports energy optimization in gait provides a rationale as to why individuals may want to minimize metabolic cost in lifting. In 2022 McAllister et al., used a dual-task paradigm that included a tone discrimination task to demonstrate how energy optimization during walking mainly involves implicit processing. Meaning that energy optimization during gait occurs with minimal cognitive attention as opposed to explicit processing, which demands conscious attention. However, no thorough explanation could be provided as to how this implicit process occurs. Noting that no significant decreases in  $\text{VO}_2$  consumption were observed post-exploration, the results of this study were therefore unable to provide further insight into how the nervous system may optimize for metabolic cost over a series of lifting bouts within a single task condition.

### **6.3. Lifting Movement Strategy**

Ultimately, we did not observe a significant reduction in biomechanical exposure or metabolic cost between the  $\text{SS}_1$  and  $\text{SS}_2$  lifting bouts in the HLLF or LLHF conditions, thus rejecting our primary hypothesis. To gain further insight as to why, a secondary analysis was

performed to quantify lifting movement strategy using the Squat-Stoop Index (SqStI) developed by Schmid (2022), as well as lift duration to quantify lifting speeds. The SqStI values observed during the HLLF condition showed that participants indeed explored a range of lifting strategies ranging from  $31.6 \pm 10.7$  (SQ) to  $82.9 \pm 9.1$  (ST), though the effect of that range was negligible on peak sagittal L4/L5 moments. The lack of change in biomechanics as a function of SqStI may explain why, after exploring a squat and stoop lifting strategy, the final preferred lifting strategy of the HLLF condition was essentially the same as the initial preferred lifting strategy.

Interestingly, the SqStI values observed during the LLHF condition resulted in a lower range than observed during HLLF trials. Two notable observations emerged. First, when comparing SqStI values during SS trials, the average SqStI values from the self-selected conditions indicate that lifters were 13% more stoop-like in the LLHF condition compared to the HLLF condition. Therefore, participants seemed to prefer a more stoop-like lifting technique when the task demands were more metabolic than biomechanical, relative to the HLLF condition where demands were more biomechanical than metabolic. Second, it's also interesting to observe that participants were able to reach almost the same average SqStI values for the ST lifting technique for both the HLLF and LLHF conditions but not for during the SQ exploration bout. Noting the trend observed in Figure 24 transitioning from a stoop to squat-like posture in the LLHF condition increased the metabolic cost considerably, such that group mean  $\text{VO}_2$  approached 30 ml/min/kg in the SQ exploration bout. Noting that participants were untrained lifters, it's plausible that participants couldn't transition to an even more squat-like posture (like the HLLF condition) because they may have been limited by their metabolic system. Overall, the SqStI values within each condition do not support our hypothesis that participants would adapt their lifting strategy after exploring a range of movement strategies. However, the initial and final SqStI values between each condition reveal interesting differences in lifting movement strategy preference between task conditions where participants preferred a lifting strategy closer to a stoop lift in the lower-load and higher-frequency condition. This is partially in agreement with past research that has found changes in lifting strategy as a function of changes in load (Sheppard, Stevenson, & Graham, 2016; Song & Qu, 2014). Therefore, our findings do support growing evidence that preferred lifting movement strategy can be modulated by task characteristics such as load and frequency.

Participants were recruited as ‘untrained lifters’ to avoid any biases in previously learned lifting movement strategies. This resulted in differences in functional personal factors such as the relative strength, flexibility, and aerobic fitness of participants. Although the mass of the load being lifted was scaled to each participant, the frequency of lifting was not scaled to participants’ metabolic capability, and so differences in relative aerobic fitness, flexibility and muscular endurance may have affected our results. Some participants may have lacked the functional capacity to explore a wide enough range of movement patterns while balancing the task demands to illicit any adaptations. A previous study looking at the differences in biomechanical exposure between lifters of varying expertise found that one of the most profound differences between groups was their physical capacities (Armstrong & Fischer, 2020). Lifters who demonstrated greater relative strength compared to the mass being lifted consistently minimized peak low back forces (Armstrong et al., 2023). This paired with the finding that expert lifters experienced less low back flexion compared to more novice lifters supports the idea that an increase in strength capacity can allow the use of a wider range of movement patterns to benefit the individual. Along the same line, lower extremity flexibility has been shown to be a limiting factor in lifting, where restrictions in ankle mobility can alter lifting kinematics and increase low back loading (Beach et al., 2012). For example, it is possible that expert lifters may exhibit greater functional ankle range of motion which allows them to adopt a lifting movement strategy that results in lower back flexion and low back loading

While growing evidence highlights links between functional capacity, range of motion and lifting mechanics, the effect of relative aerobic capacity on lifting movement strategy is not as clear. The results of this study agree with past studies that have documented the increased metabolic cost of the squat lift compared to the stoop lift (Garg & Herrin, 1979; Hagen et al., 1993; Hagen et al., 1994; Straker, 2003; Welbergen et al., 1993). Additionally, Garg & Saxena (1979) found that when participants were free to choose a lifting strategy that was most suitable to themselves, it resulted in the greatest maximum acceptable workload and the lowest metabolic work rate. However, many of these studies, including this one, lack information on the aerobic capacity of the participants. Therefore, it remains unclear how the preferred lifting movement strategy of participants may be affected by increasing levels of aerobic capacity. The study done by Garg & Saxena (1979) lacked a method to describe or quantify the ‘free style’ lifting movement strategy chosen by the participants to achieve the aforementioned benefits. By using

the Squat-Stoop Index developed by Schmid (2022), this study was able to quantitatively describe participants' self-selected lifting movement strategy in different task conditions alongside their metabolic outcomes. The results showed that in general, participants preferred a lift that was between a squat and a stoop, and that the metabolic cost was greater than a full stoop lift which goes against the findings of Garg & Saxena (1979). Ultimately, the findings of this study support that untrained lifters preferred a lifting movement strategy that was more stoop-like at lower load, but higher frequency and more squat-like when loads were higher and frequency was lower.

Lifting speed has been found to be a relevant variable during lifting, where significantly slower speeds can reduce the peak biomechanical exposures experienced at the cost of increased energy expenditure (Song et al., 2014). However, this was only observed when a fixed lifting frequency was not imposed. In this study where lifting frequency was tightly controlled for, it is likely that participants were not afforded an opportunity to explore different lifting speeds as they were required to lift and carry the load within a fixed time. This is supported by the finding that differences in lifting duration were minimal between the lifting bouts and conditions (Table 5). Therefore, this brings to light an additional lifting movement dimension that was uninvestigated in this study, where exploring different lifting speeds could have yielded potential changes in final movement patterns.

#### **6.4. Limitations**

This study offers insights on the biomechanical and metabolic determinants of lifting movement strategy, but it is not without limitation. First, although great care was taken in the selection of our primary outcome measures, they are not without limitation. The peak sagittal L4/L5 moments were calculated within the flexion-extension plane to capture low back loading. However, the repetitive lifting task performed most likely resulted in lateral bending and twisting moments that were not captured in this analysis. This is important because it is possible that the sensory feedback received by the nervous system from the lower back includes components of lateral bending and twisting.

The interpretation of the absolute  $VO_2$  consumption from the  $VO_2$  Master must be cautious as a secondary analysis of the average ventilation of participants revealed that sixteen out of fifty-two collections averaged a ventilation below the recommended 30L.min accuracy threshold (Figure 19). Of these sixteen collections, thirteen were within the HLLF condition, and

three were within the LLHF condition. A validation study done by Van Hooren et al., (2023) found that when the ventilation was lower than expected, the VO<sub>2</sub> Master tended to underestimate VO<sub>2</sub> values by up to 15%. Although this may have affected our results, a significant difference in VO<sub>2</sub> was not originally hypothesized in the HLLF condition, therefore it is presumed that this most likely had a minimal effect on the main conclusions of this study. In addition, the absolute VO<sub>2</sub> was normalized to relative VO<sub>2</sub> using participants' known body mass, however comparisons using absolute terms may have been more appropriate. Hirsch et al., 2022 demonstrated how three main assumptions should be tested when normalizing by physical characteristics, as the physical characteristics of the participants may influence the magnitudes and associated interpretations of outcome measures such as net joint moments. Therefore, noting that this study employed a repeated measures design, comparing VO<sub>2</sub> in absolute terms may have revealed additional insights into the magnitude of changes within participants, while also avoiding failed assumptions associated with ratio scaling.

Second, this study relied on principles of OFC theory to investigate lifting movement strategy, but there is no way to directly measure the process in which movement strategies are selected. Instead, this study measured the biomechanical and physiological outcomes and attempted to infer if significant differences were a result of adaptations in participants' movement strategy selection. Previous work done by Armstrong & Fischer (2020) demonstrated how we can begin to partially infer an individual's control law during lifting by using principal component analysis to investigate features of movement related to task relevant performance criterion. However, without the use of an external controller to isolate a specific movement dimension as seen in the work done by Selinger et al., (2015), it becomes difficult to fully infer an individual's control law definition.

Lastly, this study tightly controlled certain factors related to the task, while also loosely controlling for factors related to the individuals which may have influenced movement strategy. Participants were required to lift at either four lifts per minute or twelve lifts per minute. The time constraint of needing to lift and transfer the crate between the pallets may have limited the range of movement strategies they were able to explore, especially within lifting speed. This is highlighted in the lifting durations of the LLHF condition where the average lifting duration of the last ten lifts varied by at most 0.04s (Table 5). Therefore, any potential benefits of a slower or

faster lifting speed were most likely not explored by the participants due to the task constraints. In addition, there were likely differences in functional capacity within our sample population of ‘untrained lifters’, where some may have had previous experiences in physical activity that were not captured within our analyses. Experience lifting heavy loads and the ability to perceive sensory information from the low back could influence the control law of an individual (Armstrong & Fischer, 2020), and these qualities do not solely stem from experience within a weightlifting or manual materials handling environment. It is possible that participants may have unknowingly had more experience with these qualities and could have affected the group response. Although a diverse sample was important to appropriately test our hypothesis, improvements could be made by potentially binning participants into tiers of functional capacity to gain further insight into how personal factors may affect one’s lifting movement strategy selection.

## Chapter 7

### Conclusion

Understanding lifting movement strategy selection is important within the context of safe work design and MMH injury prevention. This study attempted to leverage similar research paradigms in gait by allowing participants to explore a cost landscape (perceptions vs. outcomes) where we hypothesized that participants would adapt their self-selected strategy in the SS<sub>2</sub> trial to minimize either biomechanical or metabolic outcomes accordingly, based on the task requirements. The results of this study did not support the hypothesis as biomechanical and metabolic outcomes were not significantly reduced post-exploration. Instead, a significant increase in relative VO<sub>2</sub> consumption was observed from SS<sub>1</sub> to SS<sub>2</sub>, with no significant differences in peak sagittal L4/L5 moments between SS<sub>1</sub> and SS<sub>2</sub>. A secondary analysis quantifying the Squat-Stoop Index of all lifts revealed that lifting movement strategy also minimally changed between SS<sub>1</sub> and SS<sub>2</sub> lifting bouts within each condition despite participants exploring a range of squat and stoop lifting techniques. Notably the Squat-Stoop Index during SS bouts was different between conditions, where participants had a preference toward a 13% more stoop-like lift in the LLHF condition. This provides support that the preferred lifting movement strategy of individuals is modulated by task parameters including mass and frequency, but perhaps less so by technique when lifting within specific task demand constraints.

In the future, the increase in knowledge regarding relevant performance criterion during MMH can inform more accurate human posture prediction and the development of safer ergonomic designs. This study did not provide significant evidence to support the main hypothesis, but it does provide a framework that future studies may build upon to bridge the gap between understanding the optimal control of gait to more complex dynamic movements such as lifting.

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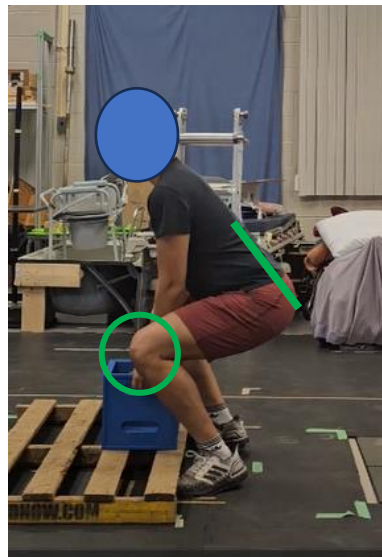
## Appendix A

### Lifting Technique Cues

Stoop Technique: “Please perform each lift by bending mostly at the waist and without too much bend in your knees”.



Squat Technique: “Please perform each lift by bending mostly at the knees and without rounding your lower back”.



Self-Selected Technique: Please perform each lift in whatever manner feels most natural to you”.

## Appendix B

### Participant Demographics Form

Height: \_\_\_\_\_ ft/inch or cm

Weight: \_\_\_\_\_ kg or lbs

Are you a kinesiology student? \_\_\_\_\_

If you are a kinesiology student, please indicate your year of study: \_\_\_\_\_

Have you prior occupational experience with manual materials handling? \_\_\_\_\_

Are you a varsity/competitive athlete? \_\_\_\_\_

Do you consider yourself to be a trained/competitive weightlifter? \_\_\_\_\_

If yes to either of the two previous questions, please indicate the average number of hours spent performing strength training per week: \_\_\_\_\_

Please indicate the average number of hours spent performing aerobic training per week: \_\_\_\_\_

# Appendix C

## Get Active Questionnaire (<https://store.csep.ca/pages/getactivequestionnaire>)



### Get Active Questionnaire

CANADIAN SOCIETY FOR EXERCISE PHYSIOLOGY –  
PHYSICAL ACTIVITY TRAINING FOR HEALTH (CSEP-PATH®)

Physical activity improves your physical and mental health. Even small amounts of physical activity are good, and more is better.

For almost everyone, the benefits of physical activity far outweigh any risks. For some individuals, specific advice from a Qualified Exercise Professional (QEP – has post-secondary education in exercise sciences and an advanced certification in the area – see [csep.ca/certifications](https://csep.ca/certifications)) or health care provider is advisable. This questionnaire is intended for all ages – to help move you along the path to becoming more physically active.

- I am completing this questionnaire for myself.
- I am completing this questionnaire for my child/dependent as parent/guardian.

PREPARE TO BECOME MORE ACTIVE	
<b>YES</b>	<b>NO</b>
The following questions will help to ensure that you have a safe physical activity experience. Please answer <b>YES</b> or <b>NO</b> to each question <b>before</b> you become more physically active. If you are unsure about any question, answer <b>YES</b> .	
<b>1</b> Have you experienced <b>ANY</b> of the following (A to F) <b>within the past six months</b> ?	
<input type="checkbox"/>	<input type="checkbox"/>
<b>A</b> A diagnosis of/treatment for heart disease or stroke, or pain/discomfort/pressure in your chest during activities of daily living or during physical activity?	
<input type="checkbox"/>	<input type="checkbox"/>
<b>B</b> A diagnosis of/treatment for high blood pressure (BP), or a resting BP of 160/90 mmHg or higher?	
<input type="checkbox"/>	<input type="checkbox"/>
<b>C</b> Dizziness or lightheadedness during physical activity?	
<input type="checkbox"/>	<input type="checkbox"/>
<b>D</b> Shortness of breath at rest?	
<input type="checkbox"/>	<input type="checkbox"/>
<b>E</b> Loss of consciousness/fainting for any reason?	
<input type="checkbox"/>	<input type="checkbox"/>
<b>F</b> Concussion?	
<input type="checkbox"/>	<input type="checkbox"/>
<b>2</b> Do you currently have pain or swelling in any part of your body (such as from an injury, acute flare-up of arthritis, or back pain) that affects your ability to be physically active?	
<input type="checkbox"/>	<input type="checkbox"/>
<b>3</b> Has a health care provider told you that you should avoid or modify certain types of physical activity?	
<input type="checkbox"/>	<input type="checkbox"/>
<b>4</b> Do you have any other medical or physical condition (such as diabetes, cancer, osteoporosis, asthma, spinal cord injury) that may affect your ability to be physically active?	
.....> <b>NO</b> to all questions: go to Page 2 – ASSESS YOUR CURRENT PHYSICAL ACTIVITY .....	
<b>YES</b> to any question: go to Reference Document – ADVICE ON WHAT TO DO IF YOU HAVE A YES RESPONSE .....	

Figure 24: Get Active Questionnaire Retrieved from <https://store.csep.ca/pages/getactivequestionnaire>

## Appendix D

### Nordic Questionnaire (Kuorinka et al., 1987)

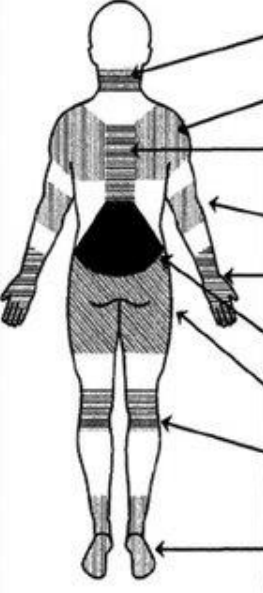
	Have you at any time during the last 12 months had trouble (such as ache, pain, discomfort, numbness) in:	During the last 12 months have you been prevented from carrying out normal activities (e.g. job, housework, hobbies) because of this trouble in:	During the last 12 months have you seen a physician for this condition:	During the last 7 days have you had trouble in:
	NECK	<input type="checkbox"/> No <input type="checkbox"/> Yes	<input type="checkbox"/> No <input type="checkbox"/> Yes	<input type="checkbox"/> No <input type="checkbox"/> Yes
	SHOULDERS	<input type="checkbox"/> No <input type="checkbox"/> Yes	<input type="checkbox"/> No <input type="checkbox"/> Yes	<input type="checkbox"/> No <input type="checkbox"/> Yes
	UPPER BACK	<input type="checkbox"/> No <input type="checkbox"/> Yes	<input type="checkbox"/> No <input type="checkbox"/> Yes	<input type="checkbox"/> No <input type="checkbox"/> Yes
	ELBOWS	<input type="checkbox"/> No <input type="checkbox"/> Yes	<input type="checkbox"/> No <input type="checkbox"/> Yes	<input type="checkbox"/> No <input type="checkbox"/> Yes
	WRISTS/ HANDS	<input type="checkbox"/> No <input type="checkbox"/> Yes	<input type="checkbox"/> No <input type="checkbox"/> Yes	<input type="checkbox"/> No <input type="checkbox"/> Yes
	LOWER BACK	<input type="checkbox"/> No <input type="checkbox"/> Yes	<input type="checkbox"/> No <input type="checkbox"/> Yes	<input type="checkbox"/> No <input type="checkbox"/> Yes
	HIPS/ THIGHS	<input type="checkbox"/> No <input type="checkbox"/> Yes	<input type="checkbox"/> No <input type="checkbox"/> Yes	<input type="checkbox"/> No <input type="checkbox"/> Yes
	KNEES	<input type="checkbox"/> No <input type="checkbox"/> Yes	<input type="checkbox"/> No <input type="checkbox"/> Yes	<input type="checkbox"/> No <input type="checkbox"/> Yes
	ANKLES/ FEET	<input type="checkbox"/> No <input type="checkbox"/> Yes	<input type="checkbox"/> No <input type="checkbox"/> Yes	<input type="checkbox"/> No <input type="checkbox"/> Yes

Figure 25: Nordic Questionnaire. Figure retrieved from Franasia et al., 2014