Design and Development of a Training System for Manual Handling Tasks in Masonry

by

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AUTHOR'S DECLARATION

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the 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.

STATEMENT OF CONTRIBUTIONS

Parts of this thesis are based on the results of collaborative research and co-authored publications as detailed here:

Chapter 3: Development of Quantitative Postural Assessment Criteria

- Ryu, J., **McFarland, T.**, Haas, C., and Abdel-Rahman, E. (2021). Automatic Clustering of Proper Working Posture. Manuscript in preparation.

  This paper is co-authored with Dr. JuHyeong Ryu and my supervisors, Drs. Carl Haas and Eihab Abdel-Rahman. I performed the original analysis of the forces and postures from the k-means clustering results and assisted with writing the paper. Dr. Ryu developed the methodology and experimental design, with supervision from Drs. Haas and Abdel-Rahman. Dr. Ryu carried out the experiments, analyzed the data and drafted the paper. Dr. Abdel-Rahman, Dr. Ryu and I collaborated on the analysis of the postural classifications in the final paper.

Chapter 4: Modeling Expert Behaviour

Ryu, J., **McFarland, T.**, Banting, B., Haas, C., and Abdel-Rahman, E. (2020). Health and Productivity Impact of Semi-Automated Work Systems in Construction. Automation in Construction, DOI: 10.1016/j.autcon.2020.10339

This paper is co-authored with Dr. JuHyeong Ryu, Dr. Bennett Banting and my supervisors, Drs. Carl Haas and Eihab Abdel-Rahman. I contributed to development of the methodology to evaluate the health and productivity impacts of semi-automation and assisted in writing the paper. Dr. Ryu developed the methodology and experimental design with supervision from Drs. Haas and Abdel-Rahman and advice from Dr. Banting. Dr. Ryu carried out the experiments, collected and analyzed the experimental data, and wrote most of the paper. Aspects of the literature review on methodologies to evaluate physical demands in the workplace were used in the literature review section of this thesis. The aspects of this paper that were incorporated into this thesis were from the pre-print edition of this paper, solely written by me, and then edited to fit the context of this thesis.

Chapter 4: Modeling Expert Behaviour

- **McFarland, T.**, Mahmassani, A., Ryu, J., Banting, B., Haas, C., and Abdel-Rahman, E. (2021, May 16-20). *Development and Implementation of Automated Apprentice Assessment Tool for Manual Handling Tasks in Masonry* [Paper presentation]. 14th Canadian Masonry Symposium (CMS), Montreal, CA.

  This paper is co-authored with my supervisors, Drs. Carl Haas and Eihab Abdel-Rahman, another master's student, Ahmad Mahmassani, as well as Dr. JuHyeong Ryu and Dr. Bennett Banting. I analyzed the data, developed the scoring system, and wrote the paper with supervision from Drs. Haas and Abdel-Rahman. Dr. Ryu carried out the experiments and collected the data used in the analysis, with advice from Dr. Banting. Mr. Mahmassani implemented the scoring system into the automated assessment tool.

Abstract

The construction industry is one of the industries with the highest rates of musculoskeletal disorders (MSDs). Masons are particularly susceptible to overexertion and back injuries due to the physical demands of their jobs. In the past, optoelectronic motion capture has been considered the 'gold standard' for motion capture in biomechanics; however, it is often not feasible for onsite data collection. Therefore, most onsite assessment tools in the industry rely on observational techniques of postures to estimate risk that cannot accurately estimate internal joint demands. Advancements in inertial measurement unit (IMU) technology have led to the development of data collection systems comparable to that of the aforementioned 'gold standard', thereby enabling the quantification of joint loads and forces on masons in the working environment. Previous research has reported that "technique" during manual handling tasks, such as lifting, can have a large impact on spinal loads. The comparison of expert and novice working techniques reveals that experts use distinct working strategies, which can lead to both lower joint forces and increased productivity. Furthermore, training based on expert work strategies has been shown to reduce exposures to biomechanical risks. Despite frequency of injuries, MSD risks are often under-prioritized in terms of safety training. Researchers emphasize a need to integrate ergonomics training within apprentices' skill training classes.

This thesis focuses on the development of an enhanced training tool and program to reduce MSD risk in apprentice masons. A novel quantitative scoring system was developed to estimate MSD risk based on the peak joint loads of expert masons. This scoring system was integrated into the enhanced training tool to better assess risk based on onsite measurement of joint loads. Furthermore, the movement patterns of novice, apprentice and expert masons were analysed to determine key characteristics of inexpert and expert techniques. These characteristics were compared to high-risk postures in the literature to establish clear postural guidelines, which were then implemented into the enhanced training tool. The tool was designed to provide evidence-based recommendations to improve posture and technique based on kinematic analyses of masons' movements. User interviews were conducted with masonry instructors to evaluate challenges, needs, and values for the training program. These insights directed the design of the accompanying educational module and overall training program. The training program and tool has the capacity to reduce biomechanical exposures of apprentice masons and increase productivity.

Acknowledgements

If I have seen further, it is by standing on the shoulders of Giants – Isaac Newton

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List of Abbreviations

A/P	Anterior/posterior
BVH	Biovision Hierarchy
CMDC	Canadian Masonry Design Centre
CMU	Concrete masonry unit
FTE	Full time equivalents
H	Height
HR	Hazard ratio
IMU	Inertial measurement unit
MMH	Manual materials handling
MOL	Ministry of Labour, Training and Skills Development
MSD	Musculoskeletal disorders
NIOSH	National Institute for Occupational Safety and Health
OMTC	Ontario Masonry Training Centre
OR	Odds ratio
REBA	Rapid entire body assessment
RR	Rate ratio
RULA	Rapid upper limb assessment

Chapter 1
Introduction

1.1 Problem Statement

The construction industry is one of the industries with the highest rates of musculoskeletal disorders (MSDs; Hess et al., 2010). Masons are particularly susceptible to overexertion and back injuries due to the physical demands of their jobs (Hess et al., 2010; Kincl et al., 2016). The high rate of MSDs can be attributed to the physically demanding occupational tasks that expose workers to heavy loads/high forces, awkward postures, and repetition (Mermarian et al., 2012; Van Der Molen et al., 2008). High rates of MSDs present a large burden to the healthcare and compensation system in Canada. Work related MSDs have negative personal, corporate, societal, and economic consequences. Despite many technological advancements in other industries, manual labor remains a cornerstone of the construction industry. Implementing ergonomic interventions in the construction industry can be complex due to the continuing manual nature of the labour and the changing work environment.

Despite frequency of injuries, MSD risks are often under-prioritized in terms of safety training. However, in the past, manual handling training or lift training has often not been an effective ergonomic intervention to reduce MSDs in the workplace (Clemes et al., 2010; Martimo et al., 2007; Verbeek et al., 2012a; Verbeek et al., 2012b). One of the main challenges is the lack of transfer of learning to the work environment or other tasks. Previous training programs have been limited by lack of integration of multidisciplinary knowledge, and relevance to the real world working conditions. On the other hand, there has been some evidence to show that training based on expert work strategies can reduce exposures to biomechanical risks (Gagnon, 2003). The comparison of expert and novice working techniques reveals that experts use distinct working strategies, which can lead to both lower joint forces and increased productivity (Alwasel et al., 2017a; Ryu et al., 2020a). Furthermore, technique during manual handling tasks, such as lifting, can have a large impact on spinal loads. Researchers emphasize a need to integrate ergonomics training within apprentices' skill training classes.

Many countries, including Canada, have health and safety legislation that requires employers to provide education and training on MSD risks. Notably, training was found to be the most cost-effective ergonomic intervention based on economic value (Lahiri et al., 2005). While training may not be an ideal sole solution, it may provide value as part of an overall ergonomic approach. Apprentice masons could benefit from a tailored, evidence-based, industry-relevant, training program to increase overall awareness and education on MSDs, but also to improve their lifting techniques to reduce exposures to MSD risks.

1.2 Previously Developed Onsite Assessment Tool

The research described in this thesis builds directly on previous research in which an ergonomic assessment tool was created to capture biomechanical motion data from masons on-site and to evaluate joint loads and muscle injury risk (Diraneyya, 2019). IMU sensors are worn by the participant while completing a task and the output from the IMU sensor system is processed by the assessment tool software. The participant is also filmed on video, to visualize the recorded movements, alongside the kinematic data. Additional information is input into the software program manually, such as the participants' height and weight, as well as the timestamps and hands associated with manual handling. After task completion by the participant, the assessment tool uses inverse dynamics to estimate the net joint forces and moments, namely lower back compression force and shear forces at the L4/L5 disc, shoulder, elbow, hip, knee and ankle. The tool generates a report, Figure 1, which identifies critical time segments where the loads on the joints are particularly high and provides a video replay of the at-risk movement, a graph of the joint moment including those critical points, and a colour-coded stick figure to represent the risk at various joints in the body.

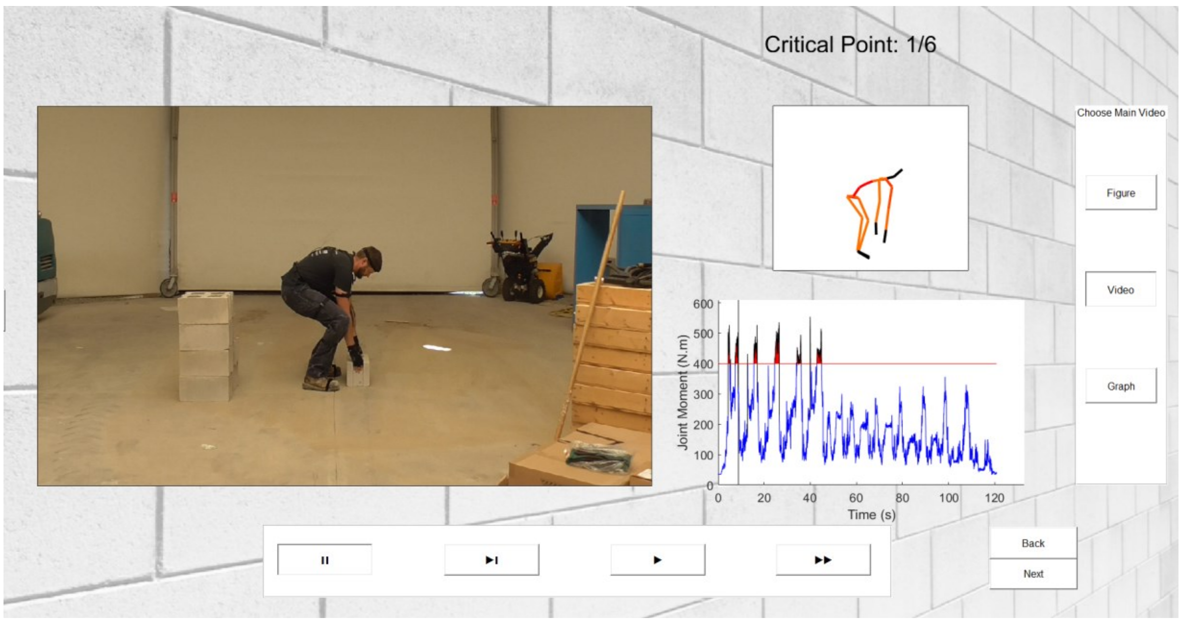


Figure 1: Graphical Interface of the Assessment Tool Critical Point Report

The enhanced assessment tool enables the evaluation of risk directly from estimated forces and moments measured while masons are working on-site. This is especially novel, given that many onsite assessment tools in the industry still rely on observational techniques of postures to estimate risk, e.g., RULA, REBA, and are not suited for manual materials handling tasks (Ryu et al., 2021). However, further improvements to the tool are still necessary. In the absence of established thresholds for joint moments and forces, the assessment tool used an arbitrary threshold of 80% of the peak force or moment to act as criteria for defining critical time segments. The tool also reported the loads at the critical points in N or N•m, which without context, is not meaningful to masons without expertise in biomechanics. Additionally, while the assessment tool can identify points of high joint loads, it has limited, knowledge-based, connection to injury risk.

1.3 Proposal for a Training System

The previously developed assessment tool can provide value to health practitioners and site-managers by identifying high joint loads. However, those without knowledge in ergonomics may have difficulty translating that information into actionable steps to reduce injury risk in the workplace. Furthermore, the tool is unable to identify which movements are high risk, and it cannot provide recommendations to reduce the risk. To augment the benefits of the tool and improve its practicality for implementation in masonry training centers, the tool should be redesigned for training. By focusing on kinematics in addition to kinetics, the redesigned tool will be able to identify high-risk postures and it will provide feedback to reduce joint loads and potential injury risk in apprentice masons. The semi-automated training tool should be accompanied by an implementation plan and associated educational resources and program to constitute a full training system.

While the focus of this research is within the masonry sector, similar approaches have been studied in the healthcare sector with successful outcomes. A recent study found that a semi-automated assessment tool used during simulated patient handling training was able to reduce end-range lumbar spine flexion (Owlia et al., 2019). This system used sensors to provide real-time biofeedback based on participants' spine posture, alerting them when spine flexion exceeded a certain threshold.

1.4 Research Objectives and Contributions

The goal of this thesis is to design and develop a practical training program for apprentice masons, using the redesigned training tool, to teach safe lifting techniques and reduce the risk of musculoskeletal disorders. The training program will not only focus on the training tool but provide the instructors accompanying resources for implementation as well. The research objectives for this thesis include:

1. Establish evidence-based quantitative thresholds to assess MSD risk based on forces and moments at joints throughout the body.
2. Analyze the movements of novice, apprentice, and expert masons to characterise postural characteristics of inexpert and expert techniques.
3. Review the literature and characterisation of inexpert and expert techniques to develop quantitative postural assessment criteria for use in the enhanced training tool.
4. Redesign assessment tool into a training tool, by integrating risk and postural assessment criteria and developing recommendations for best lifting practices.
5. Develop a comprehensive training program, including resources required for implementation.

The main contribution of the thesis is the design of a tailored training program, tool, and resources to reduce MSD risk in apprentice masons for implementation in Ontario masonry training centers. This thesis also contributes to the literature through the presentation of a novel quantitative biomechanical assessment and scoring system for MSD risk in masons, and the in-depth kinematic analysis of masonry techniques by experience level.

1.5 Scope

This research was conducted for the Canadian Masonry Design Centre (CMDC) and the Ontario Masonry Training Centre (OMTC), and the final training program was designed to accommodate stakeholders' wishes and constraints. The training tool was designed to provide recommendations based on the task of building a standard wall, and not other masonry tasks. The focus of the training tool development was to turn the previously developed assessment tool into a tool with suitable application for a training context. Therefore, improvements were constrained within the framework of the original technology and functionality rather than striving to make large improvements to the technological capabilities.

1.6 Methodology

The development of the scoring system and the design of the training tool and program was based on both primary and secondary research including new analyses on previously collected raw experimental data, user interviews with stakeholders and masonry instructors, and a review of the literature from multiple disciplines.

1.7 Thesis Organization

The organization of this thesis is described below:

Chapter 2 provides a comprehensive review of the literature on musculoskeletal risks in masonry, studies on manual materials handling training, best practices in ergonomics training, novice versus expert performance during manual handling tasks, motor learning principles, adult learning principles and behavioural change models for health promotion.

Chapter 3 starts by reviewing the literature for existing postural thresholds and guidelines. Then the chapter dives into a postural analysis of movement techniques in masonry by experience level. The postural analysis is conducted using 3 different methods: predictor screening, statistical analysis, and k-means clustering. Lastly, these insights are integrated to develop quantitative postural thresholds for apprentices.

Chapter 4 reviews the current methods for onsite risk assessment in the industry, followed by a description of the methods used to develop a scoring system used to model expert lifting behaviour in masonry based on the measurement of onsite biomechanical data.

Chapter 5 summarizes the findings from qualitative user interviews with CMDC stakeholders and OMTC instructors. The results are split into two sections, the first concerning ergonomics knowledge and attitudes in masonry to capture the existing culture in the industry and the apprentice training courses. The second focuses on feedback to inform the design of the training tool and program.

Chapter 6 describes the development process of the training tool and the training deliverables. The design brief is outlined, followed by an elaboration on the training program itself, including the design of the onsite training tool and the in-class educational modules and resources.

Chapter 7 concludes the thesis by summarizing the outcomes of the research, the contributions to knowledge, the limitations of the research and recommendations for future research.

Chapter 2
Literature Review

2.1 Musculoskeletal Disorder Risks in Masonry

The construction industry is a leader in musculoskeletal disorders (MSDs) (Hess et al., 2010; Merlino et al., 2003). Masonry has one of the highest rates of overexertion and back injuries, reported to be 43-66.5 and 45.3-75.4 injuries per 10,000 full time equivalents, respectively (Hess et al., 2010; Kincl et al., 2016). Masonry apprentices are often assumed to be healthy as new workers in the trade; however, a recent study found that 78% of apprentices reported musculoskeletal symptoms (Anton et al., 2020). Notably, apprentices reported musculoskeletal symptoms at a rate comparable to those of journeymen. The high rate of MSDs can be attributed to physically demanding tasks, such as manual material handing (MMH) (e.g., lifting), that expose workers to risk factors such as heavy loads, awkward postures, and high repetition (Mermarian et al., 2012; Van Der Molen et al., 2008; Kumar, 2001). On an average day, masons may lay between 240 to 294 concrete blocks weighing 11-16 kg, resulting in manual handling of cumulative loads up to 3840 kg per day (Gallagher and Heberger, 2013). In brick laying work, masons may lay down an average of 1,000 bricks per day (Mitropoulos and Memarian, 2012; Schneider and Susi, 1994). Repetition is a concern since it has been shown to interact with force to increase MSD risk through a fatigue failure process in the tissues (Kumar, 2001; Gallagher and Heberger, 2013). While there are some challenges in demonstrating the epidemiological link between physical exposures and MSDs, the research linking these physical exposures to MSDs is adequate (Punnett and Wegman, 2004). There is evidence to support the link between exposures to manual material handling, frequent bending and twisting, heavy physical load, force, repetition and a combination of repetition and force during work with MSD risk at the low back and upper extremities (Bernard and Putz-Anderson 1997; Punnett and Wegman, 2004). MSDs are associated with pain, disability, absenteeism and productivity and quality losses (Ministry of Labour, Training and Skills Development [MOL], 2019c; Sadosky et al., 2015). High rates of MSDs present a large burden to the healthcare and compensation system in Canada; in Ontario alone, MSDs account for the number one cause of lost-time injuries, and cost hundreds of millions of dollars (MOL, 2019c). The direct and indirect total burden of musculoskeletal diseases on the Canadian economy has been estimated at $19.7 billion dollars (Mirolla, 2004).

Despite frequency of injuries, MSD risks are often under-prioritized in terms of safety training. In the US construction industry, 91% of companies had a written safety program, but only 69% had a lifting program and only 34% had an ergonomics program (Choi, 2012). In a study of Hispanic construction workers in the US, 44% reported no formal safety training, 24% reported some while 17% and 4% reported attending Occupational Safety and Health Administration 10-hour and 30-hour certification training, respectively (McGlothlin et al., 2009). Ergonomics training is also lacking in apprenticeship programs (Kincl et al., 2016) despite recommendations for its inclusion at the apprenticeship stage (Kincl et al., 2016; Jensen and Kofoed, 2002). In a study evaluating risk mitigation strategies in the construction sector, a panel of experts estimated the impact of safety and health orientation and training to reduce frequency and severity as a 4 and 3, respectively, for both incidents due to overexertion and incidents due to repetitive motion, according to a specialized scale (Hallowell and Gambatese, 2009). The impact of safety and health orientation and training for risk mitigation of overexertion injuries was second to upper management support, project specific training, employee involvement, job hazard assessments, frequent worksite inspections, substance abuse programs, and having a safety manager on site, whereas for repetitive motion injuries, training was second to project specific training, employee involvement, job hazard assessments, frequent worksite inspections, safety and health committees, safety manager on site (Hallowell and Gambatese, 2009). Overall, experts perceived safety training had a place for risk mitigation in construction.

2.2 Manual Materials Handling Training

The consensus in the literature is that there is little evidence to support manual handling or lift training as an effective ergonomic intervention in the workplace (Clemes et al., 2010; Martimo et al., 2007; Haslam et al., 2007; Hogan et al., 2014; Verbeek et al., 2012a; Verbeek et al., 2012b). A lack of evidence has been shown for both education- and awareness-based training, as well as technique-based strategies across different industries (Clemes et al., 2010; Martimo et al., 2007; Haslam et al., 2007; Verbeek et al., 2012a; Verbeek et al., 2012b). Several systematic reviews also found that training combined with other ergonomic interventions such as lifting aids were ineffective at reducing MSDs (Hogan et al., 2014; Martimo et al., 2007; Verbeek et al., 2012a). Training modalities included in the studies reviewed were traditional lecture-based learning, coaching sessions, video review, and biofeedback, among others. The literature on training is highly varied with training programs ranging from a single 1-hour session up to weekly sessions (1 hour) over the course of 2 years with supplementary meetings (Clemes et al., 2009; Martimo et al., 2008; Verbeek et al., 2012a; Verbeek et al., 2012b; Haslam et al., 2007; Hogan et al., 2014). Despite increasing understanding and knowledge in workers (Hogan et al., 2014), training content is not being applied to work scenarios (Clemes et al., 2009; Haslam et al., 2007; Hogan et al., 2014, Beach et al., 2014; St-Vincent et al., 1989). The overall conclusion is that redesigning the work environment has a greater potential to reduce MSD risk compared to training (Plamondon et al., 2012; Plamondon et al., 2014). For further information on training studies and results see Appendix A.

On the contrary, exercise training was found to have beneficial short-term effects to increase individual capabilities (i.e., strength and flexibility; Clemes et al., 2009; Beach et al., 2014). While generalized exercise training could improve capacity for a greater variety of tasks, task-specific exercise training was able to produce larger improvements in the targeted manual material handling task (Knapik and Sharp, 1998). Generalized physical training may be more effective for jobs with a variety of tasks and require workers to maintain high levels of physical capacity to respond to emergency scenarios (e.g., military or firefighting) (Knapik and Sharp, 1998). For example, in an exercise intervention study to evaluate impact on physical fitness and occupational load back loading, a group of firefighters completed either an exercise program designed to maximally improve fitness, or an exercise program to maximally improve fitness alongside extensive coaching on proper movement strategies (Beach et al., 2014). While both exercise intervention groups experienced significant improvements in many markers of physical fitness and health (body composition, cardiorespiratory fitness, muscular strength, power and endurance and flexibility), their low-back loading responses to simulated job-specific tasks were not consistently impacted compared to each other or the control group

(Beach et al., 2014). However, recommending physical fitness interventions to heavy labor jobs may not be well accepted by the workers (Haslam et al., 2007; McGill, 2015), which is especially pertinent in the construction sector. Additionally, for physically demanding jobs, rest periods need to be longer to provide adequate recovery (McGill, 2015).

While many studies report no differences in injury rates, several articles looking at biomechanical exposures did find post-training improvements (Clemes et al, 2009; Martimo et al., 2008). Manual material handling training during simulated lifting tasks resulted in a reduction in peak compression forces at the low back (Agruss et al., 2004), 3D spine moments (Lavender et al., 2002), muscular activation (Gross, 1984), mechanical work and back efforts by 10-30% (Gagnon, 2003). Improvements were also reported in studies with training and education supplemented with additional MSD prevention strategies. Brown et al. (2002) investigated the impacts of a back-pain management program which consisted of education and awareness of lifting and handling, risk assessment and fast-track physiotherapy. Following the 12-month workplace intervention, warehouse employees reported reduced musculoskeletal discomfort and a 56% reduction in sickness absence due to back pain (Brown et al., 2002). In an intervention study of an auto parts manufacturer, the implementation of an applied ergonomics program featuring management support, MMH equipment and administrative intervention training and health education, low back muscular loads in the intervention group were significantly reduced (Poosanthanasarn et al., 2005). It is possible that the perceived lack of effectiveness corresponds to inherent job risk and cumulative physical demands rather than manual handling or changes in biomechanical exposures. Verbeek et al. (2012b) hypothesized that the risk of back pain may be related to "other work-related factors inherent in the populations studied (such as non-neutral, bent, or rotated trunk postures without lifting or handling, or psychosocial strain)". Furthermore, the absence of significant effects may indicate that injury rates are insensitive to the impacts of training and are inadequate as an indicator for effectiveness (Yassi et al., 2001). Therefore, evaluating the reduction in biomechanical risk exposure may be a more promising strategy to evaluate interventions, due to the multifactorial nature of MSDs (ISO, 2012). Furthermore, reductions in mechanical exposures have been recommended to evaluate primary interventions in addition to health outcomes to provide better insight into dose-response relationships between MSD risk factors and MSDs (Lötters and Burdof, 2002).

The main challenges of training in previous research have been the lack of transfer of learning to the work environment and a lack of transfer to other untrained tasks (Clemes et al., 2009; Haslam et al., 2007; Hogan et al., 2014, Beach et al., 2014; St-Vincent et al., 1989). Potential reasons why training is often unsuccessful to change movement behaviours are that (1) workers tend to resume old habits without reinforcement or refreshment of training; (2) task-specific training typically creates improvements for only the task in question; (3) training often occurs in environments and scenarios with optimal conditions and may not consider other barriers and realities of the working environment; and (4) training will not reduce inherent risks in the job if the physical demands or exposures remain unchanged (Clemes et al., 2009; Kroemer, 1992; Stubbs et al., 1983).

However, a limiting factor of several of the reviews were the low quality of papers appraised (Clemes et al., 2009; Martimo et al., 2008; Verbeek et al., 2012a). Direct comparison between studies on the impact of training can be difficult due to the variability of training strategies, and measured outcomes, which range from biomechanical to subjective to observational. Additionally, many intervention studies combine multiple approaches which may introduce confounding effects and mask the cause of the improvement. A systematic review by Hogan et al. (2014) reports that there has been little research investigating the effectiveness of training on transfer of training and behavioral change; many studies used self-reported measurements that are inadequate to assess behavioral change. Recommendations for future studies include high-quality randomized studies, standardized outcome measurements, more scientific rigour and appropriate power, larger sample sizes and follow-up periods of longer than 6 months (Verbeek et al., 2012a; Martimo et al., 2007; Clemes et al., 2010). Beach et al. (2014) suggest that single subject experimental designs may be advantageous to detect movement changes obscured by inter- and intra-subject variability. Additionally, a recent paper focusing on the pitfalls of recent literature regarding the value of manual material handling training noted several additional limiting factors of the review findings (Denis et al., 2020). Denis et al. (2020) found that there was a lack of reporting on training program characteristics like size of organization, trainers' profiles, participant information and an overemphasis on a singular safe technique.

Many countries, including Canada, have health and safety legislation that requires employers to provide education and training on MSD risks (Council directive 90/269/EEC; Occupational Health and Safety Act, 1990; Martimo et al., 2007). Under Ontario's Occupational Health and Safety Act (1990), clause 25(2)(a) and (h), employers are required to "provide information, instruction and supervision to a worker to protect the health or safety of the worker" and "take every precaution reasonable in the circumstances for the protection of a worker", respectively. This includes the education and awareness of MSD hazards as well as the protection of the worker from MSD risk, which may comprise of training on safe work methods, manual material handling techniques, patient handling techniques, use of mechanical lifting aids, other equipment and recognition and reporting of MSD hazards, among other workplace interventions (MOL, 2019a; MOL, 2019b). On the other hand, manual material handling training requirements are more explicitly stated in 'Council directive 90/269/EEC' (1990) from the Council of European Communities, that employers are required to provide "proper training and information on how to handle loads correctly and the risks to which they might be exposed". In order to fulfill their legal obligations, employers continue to provide workers with MMH training despite doubts concerning the effectiveness of lifting and MMH training programs (McDermott et al., 2012; US Department of Health and Human Services [DHHS], 1981). Therefore, it may be better to spend efforts to improve existing practices (DHHS, 1981). Nevertheless, a study analyzing the economic value of ergonomic interventions, including training, engineering controls and comprehensive MSD programs, found that training was the most cost-effective intervention in 17 global sub-regions (Lahiri et al., 2005). Therefore, training can be an important step towards reducing MSD risk (Lahiri et al., 2005). It should be noted however, that alternative viewpoints position ergonomic interventions that rely on behaviour change only, such as training or team lifting initiatives, behind the effectiveness of other types of interventions, that eliminate or reduce exposure or reduce time of exposure, based on both MSD-related outcomes and cost-benefit outcomes (Goggins et al., 2008).

To develop a MMH training program with the greatest potential for effectiveness, it is critical to not only understand the best practices from the field of biomechanics and ergonomics, but integrate best practices from other domains as well, such as motor learning, adult learning, and health promotion models for behavioural change. This information can then be contextualized within the construction sector for training applications. While education and training are essential for workers to understand and mitigate risks from manual handling, promote safety culture and promote behavioural changes, training is not recommended nor effective as a control strategy alone and should always be provided within the framework of a larger MSD prevention program and other workplace interventions (ISO, 2012; MOL, 2019b).

The objective of this review is to support multidisciplinary knowledge integration from the fields of ergonomics, motor learning, adult learning, and health promotion to outline best practices for manual material handling training with respect to the construction industry. Workplace redesign, lifting equipment, good health and safety and MSD prevention policies are recommended to address risk. The scope of this review; however, is solely aimed towards outlining best practices for the development of an MMH training program.

2.3 Best Practices in Training

Evidence exists to support the effectiveness of the following MMH training approaches: exercise training, using a multidimensional approach, training workers and managers to assess and report MSD risks, tailoring the training to the participants, observing workers in their working environment, and comparing the strategies of novice and expert workers (Haslam et al., 2007; Gagnon, 2005; ISO, 2012; Clemes et al., 2009; Gagnon, 2003). Reviewing the gaps in recent research, manual handling training can be improved by de-emphasizing a singular safe technique, rather teaching participants to choose appropriate actions based on the scenario and organize their work (Denis et al., 2020). Improved manual handling training should also encourage practice using real world situations adapted to different difficulty levels and change conditions in which handling takes place (Denis et al., 2020).

A few sources exist that aggregate professional opinion on best practices for manual material handling. In one study, guiding principles for effective manual handling training was investigated through literature surveys, 150 telephone interviews from a range of industrial sectors, as well as two expert panels featuring 25 experts on occupational health, ergonomics, health and safety, organizational behaviour, and manual handling, as well as other key stakeholders (Haslam et al., 2007). A 9-year project gathered expert opinions on lift training from health professionals at conferences totalling over 900 attendees (Sedgwick and Gormley, 1998). Lastly, an ISO technical committee published an international consensus on manual handling practices specific to the handling of people in the healthcare sector; however, general principles from this guideline can also be applied to manual material handling across other sectors (ISO, 2012). Best practices for MMH training based on expert consensus from the three sources were theoretical and hands-on practice, sufficient time allocation to training, comprehensive training of all new staff and management, tailoring the training to the workers and workplace, training based on risk assessment and core competencies, reinforcing the training, refresher courses, more frequent retraining and support of workers, maintaining appropriate records, supervision and evaluation and adequately qualified trainers and external training consultancies and the application of principles of adult learning, behavior modification and skill learning (Haslam et al., 2007; Sedgwick and Gormley, 1998; ISO, 2012). **Out of all the recommendations from various expert groups, the common guiding principles recommended by all sources were the need for: (1) practice, (2) tailoring the training, (3) reinforcement and refresher courses.**

Practice is an important aspect of skill learning and is needed for the individual learn how to carry out the skill. The element of practice with respect to motor learning will be discussed more in depth in Section 2.5.1. With respect to customization of the training program, training must be tailored to both the workers and the work environment, with a consideration of knowledge and awareness of risks, and it should be developed only after previous observation of workers in their work setting (Haslam et al., 2007; Whysall et al., 2006; Whysall et al., 2007; McDermott et al., 2012). Reinforcement is important to re-emphasize and reiterate the training taught. Reinforcement may also help to reduce the occurrence of one of the failure modes for training, which is that individuals revert to old patterns. Reinforcement or refresher training is recommended to occur at least once every 3 years (ISO, 2012).

Furthermore, 90% of health professionals suggested that MMH training should apply the principles of motor skill learning, while 71% agreed that MMH training should apply principles of adult learning and behaviour modification (Sedgwick and Gormley, 1998). General principles of skill learning as noted by Sedgwick and Gormley (1998) include understanding and introducing the structure of the skill, practicing extensively over a multi-week period with progressive complexity, and providing constant feedback and objective benchmarks for learning. Principles of adult learning and behaviour modification include developing an understanding of the training context and individual motivation for change, increasing lifting capacity (i.e., skill and physical fitness), tailoring the training to reflect workers' previous knowledge and experience and refreshing the training (Sedgwick and Gormley, 1998). One of the limitations of the studies included in one of the systematic reviews was that none utilized behaviour change models for their training program, suggesting that knowledge integration from the health promotion field is lacking from current training approaches (Verbeek et al., 2012b).

To summarize, practice, reinforcement and customization are 3 of the most essential components of MMH training as agreed upon by health professionals and key stakeholders. There is some evidence to suggest that training based on the observation and adoption of expert working strategies is effective for reducing physical exposures to MSD risks. **Lastly, current training practices could benefit from integrating principles from other fields such as motor skill learning, adult learning, and behavioral change.** In the following sections, key findings on novice and expert manual handling techniques, motor learning, adult learning and behavioral change models will be reviewed.

2.4 Novice vs. Expert Manual Material Handling Strategies

The literature on novice and expert handling techniques can be divided into 3 main categories: (i) biomechanical analysis and comparison of expert and novice manual handling strategies, (ii) biomechanical analysis of expert strategies, and (iii) training based on the observation of expert strategies.

2.4.1 Comparison of Expert and Novice Strategies

Previous studies in masonry found that journeymen with over 5 and over 20 years of experience have reduced exposures to body loads and are more productive as compared to less experienced workers (novices and apprentices: Alwasel et al., 2017a; Ryu et al., 2020a). Furthermore, experienced journeymen were found to adopt distinct work techniques from less experienced workers (Alwasel et al., 2017b; Ryu et al., 2020a). These findings provide a basis for training apprentice masons centered on expert work strategies as a potential intervention to reduce MSD risk while balancing productivity needs. However, the characteristics of expert techniques have not yet been thoroughly analyzed in the literature. Further research must identify key characteristics of expert strategies that contribute to both lower body loads while maintaining higher productivity in order to establish training guidelines.

The analysis and comparison of both novice and expert biomechanics in the literature on MMH have identified differences in the way that they perform manual handling tasks, including stepping strategies, feet and body positioning, knee postures, trunk inclination, spine postures, spinal loading, lumbar moments, hand and box positioning, muscle activity, strength, oxygen saturation and productivity. However, it should be noted that there is no standard definition for ‘expert’ or ‘novice’ (Plamondon et al., 2014). In the literature, many of the experienced workers only have a minimum of 1-3 years of experience (Lee and Nussbaum, 2012; Lee et al., 2014a; Lee and Nussbaum 2013; Lee et al., 2014b; Yang et al., 2007; Marras et al., 2006). In a study analysing the biomechanical differences of masons, journeymen (masons with over 5 years of experience), and novices (<1-year experience) had the lowest injury risk followed by 1st year apprentices while 3rd year apprentices had the highest injury risk (Alwasel et al., 2017a). This shows an important trend in masonry, where novices are at lower risk than 1st and 3rd year apprentices. This may not be the case for all trades; however, given this evidence, it is important to make a distinction between experienced workers with fewer than 5 years of experience and experts. Boocock et al. (2015) describes the impact of experience on manual handling strategies in a systematic review but does not make a distinction between expert and experienced workers. For further information on expert versus novice performance in manual handling tasks see Appendix B.

2.4.2 Biomechanical Analysis of Expert Strategies

While many studies examine the differences in working techniques of experienced and novice workers, few assess the biomechanics of expert techniques or analyze training based on expert techniques. Delisle et al. (1996a; 1996b, 1998; 1999) conducted several experiments analyzing the lifting strategies of experts replicated by novices to understand the biomechanical consequences of the strategies including box tilting, footstep strategies, knee flexion and lateral foot spacing during box handling tasks. These expert strategies were based off findings comparing expert and novices in previous studies. For a more in-depth review of expert strategies found in these studies, see Appendix B.

2.4.3 Training Based on Observation of Expert Strategies

Lastly, one study looked at the efficacy of a training model based on expert strategies (Gagnon, 2003). The participants were taught basic biomechanical principles about lifting, then they watched a video that comparing expert strategies to novice strategies, focusing on footwork, handgrips, load tilting and posture. The participants were then allowed to practice by lifting 16 boxes using a 'search' strategy. Participants were given some feedback in the first few trials only, and encouraged to try out different strategies of lifting, and ultimately decide upon a technique based on personal preference. The study found that training reduced mechanical work and back extensor moments, but did not affect back asymmetry, and that training also transferred to a novel (untrained) analogous lifting task (Gagnon, 2003). Furthermore, in a control study, novice workers did not significantly change their strategies during free practice without additional instructions (Gagnon, 2005). The transfer of training to a novel task shows evidence of motor learning that can be applied to other scenarios. This is especially important given that one of the major barriers for effectiveness of training is transferability of learned skills to untrained tasks.

2.5 Motor Learning Principles

Motor learning corresponds to the learning of physical movements or skills. This can range from a child learning how to walk, a patient learning how to pick up an object with a prosthetic in occupational or physical therapy, or an athlete learning how to improve their golf swing. Since our goal for training is to teach apprentices how to move in a certain way (in particular, replicate aspects of expert techniques), it is critical to understand the most effective way to teach movement. When discussing learning, acquisition refers to the initial learning of the new skill, while retention refers to retaining the ability to do the skill over time, and transfer refers to applying the skill to other contexts or tasks, that were not initially trained. Alternatively, acquisition refers primarily to performance, while retention and transfer signifies learning. Multiple factors play a role in the effectiveness of motor learning. Four important such factors are practice, feedback, focus of attention and instruction.

2.5.1 Practice

Practice refers to the hands-on application of a theory, method, or skill. In motor learning, it often involves repeated instances of physically carrying out the skill. Practice is necessary for skill improvement (Salmoni et al., 1984; Sharma et al., 2016; Williams and Ford, 2008; Wu et al., 2011; Poole, 1991). The theory of deliberate practice asserts that expertise is proportional to the time spent practicing a skill; however, improvement comes only from deliberate effort to change performance rather than just routine repetition (Williams and Ford, 2008). This was demonstrated in the lifting study by Gagnon (2005) in which free practice (non-deliberate practice) by novices did not lead to any improvements in lifting performance. Williams and Ford (2008) state that "for effective learning, practice must be challenging in relation to its level of difficulty, informative due to the availability of feedback, and repetitive with opportunity for error detection and correction". Therefore, for skill improvement, instructions, training, and feedback is necessary.

There are also different methods of practicing: blocked practice and random practice. Blocked practice refers to practicing one skill or task repeatedly without interruption, whereas random practice refers to practicing multiple skills or tasks interspersed with other skills or tasks and varying the sequence in which they are presented. Blocked practice was found to have better performance in the acquisition phase; however, random practice was found to increase retention and transfer (Vickers et al., 1999; Wu et al., 2011; Poole, 1991).

2.5.2 Feedback

Feedback is one of most important elements of skill learning (Salmoni et al., 1984; Sharma et al., 2016; Poole, 1991). In fact, it was found that giving beginners advice based on expert performance can improve learning (Wulf et al., 1998). There are two categorizations of feedback: knowledge of results (KR), which provides information about success in reaching an environmental goal, and knowledge of performance (KP), which provides information about the individual's movement form while trying to reach that goal (Salmoni et al., 1984).

KR is essential for skill acquisition and learning (Salmoni et al., 1984). KR has been shown to enhance performance but can degrade learning if given too frequently (Salmoni et al., 1984). However, self-estimation of movement form, alongside KR, can improve skill learning (Liu and Wrisberg, 1997). Alternatively, KP is shown to improve learning for closed motor skills (skills that are performed independent of the environment; Wallace and Hagler, 1979). KP may be more effective than KR, particularly in cases where KR is redundant (Zubiaur et al., 1999; Sharma et al., 2016). KR may be redundant when the results are an environmental goal that is easily perceived by the participant themselves. One study found that a lower relative frequency of KP improved acquisition, retention, and transfer of a motor skill (Weeks and Kordus, 1998). For KP, spatial information was also more effective than temporal information (Young and Schmidt, 1992).

There are also different benefits depending on when or how frequent the feedback is given. Short delays between the completion of the task and administration of KR feedback decreases learning (Salmoni et al., 1984; Liu and Wrisberg, 1997; Swinnen et al., 1990; Schooler and Anderson, 1990). It has been suggested that the time delay allows for the development of error detection and self-correction abilities by the learner (Schooler and Anderson, 1990). Similarly, a lower relative frequency (number of trials with feedback/total number of trials) of KR or KP can benefit learning (Salmoni et al., 1984; Weeks and Kordus, 1998). A faded feedback schedule, with more feedback at the beginning of skill acquisition, and a lower frequency of feedback over time, also improves learning (Nicholson and Schmidt, 1991; Vickers et al., 1999). In some cases, when the learner was given the choice of whether to receive feedback after each trial (subject-controlled feedback), learning improved (Janelle et al., 1995; Li et al., 2015; Chiviacowsky and Wulf, 2002; Chiviacowsky and Wulf, 2005). Interestingly, in a study on subject controlled feedback, participants most often asked for feedback following good trials, while in another, participants also had smaller errors on trials even if they requested feedback before the trial (Chiviacowsky and Wulf, 2002; Chiviacowsky and Wulf, 2005). This demonstrates a motivational potential for feedback as well (Chiviacowsky and Wulf, 2002).

2.5.3 Focus of Attention

Another aspect that affects performance is the individuals focus of attention when completing a skill. For example, the focus of attention can be external (impact on the environment) or internal (within the body). The body of literature over the past 15 years shows overwhelmingly that an external focus of attention improves motor performance and learning compared to an internal focus of attention (Wulf, 2013). An internal focus does not necessarily degrade learning, rather, it does not differ from control conditions. An external focus of attention enhances motor learning in beginners and experts (Wulf and Su, 2007; Wulf et al., 1998; Wulf, 2013). In one study, providing externally focused feedback after every trial improved learning more than after every third trial (Wulf et al., 2010).

2.5.4 Instruction

When it comes to instruction, giving novices advice based on expert performance can also improve learning (Wulf et al., 1998). Additionally, for novices, simpler behavioural training models featuring simple-to-complex instruction, focus on basic components of skills before combining them, variable practice and frequent feedback is more beneficial for acquisition and transfer in skill learning (Vickers et al., 1999). On the other hand, for intermediate and expert level performers, decision training with complex instruction, variable practice and a faded feedback schedule reduces performance during acquisition but performs better in transfer, indicative of improved learning (Vickers et al., 1999).

2.6 Adult Learning Principles

Within the adult education literature, a set of best practices for adult learning emerges. These include explaining the training objectives at the beginning, making the content relevant and useful as well as practical for workplace conditions, ensuring group interactivity, and using a variety of techniques including active participation and hands-on problem solving (Bryan et al., 2009; Collins, 2004; Galbraith and Fouch, 2007; Palis and Quiros, 2014). The training should also explain the reason for training and an understanding of the training context and process, incorporate reflection, feedback, and reinforcement, as well as regular refreshment of content (Bryan et al., 2009; Collins, 2004; Galbraith and Fouch, 2007; Palis and Quiros, 2014; Sedgwick and Gormley, 1998). Learning approaches should match the background and diversity of the participants and must respect and build upon the participants' previous knowledge and experiences (Bryan et al., 2009; Collins, 2004; Palis and Quiros, 2014; Sedgwick and Gormley, 1998).

2.7 Behavioural Change Models for Health Promotion

Ergonomic interventions could be improved by integrating principles of health promotion for behaviour change and education (Whysall et al., 2007; Haslam, 2002). Studies on manual handling training to reduce MSD risk were criticized in a systematic review for lack of utilization of more elaborate models for health behavioural change, specially suggesting models such as the stages-of-change model, the protection-motivation theory or the theory of reasoned action and planned behavior (Verbeek et al. 2012b).

The transtheoretical model (TTM) of behaviour change (also known as the stages of change model) theorizes that change is a process that occurs through six stages, but not necessarily linearly (Prochaska et al., 2015). These stages include precontemplation, contemplation, preparation, action, maintenance, and termination (Prochaska et al., 2015). To move through each stage, evidence supports 10 processes of change (Prochaska et al., 2015). These include 1) increasing awareness that support the healthy behaviour change; 2) experiencing negative emotions associated with the unhealthy behavioural risks; 3) realizing the negative impact of the unhealthy behaviour or positive impact of the healthy behaviour on one's social or physical environment; 4) associating the behaviour change with personal identity; 5) committing to change; 6) seeking social support to change; 7) substituting healthier behaviours for unhealthy behaviours; 8) positive and negative reinforcement; 9) removing or adding cues to support behaviour change; and 10) realizing that social norms support the healthy behaviour change. Processes 1-3 are associated with the transition between the precontemplation and contemplation stages, process 4 is associated with the transition between the contemplation and preparation stage, 5 is associated with the preparation and action stage, while processes 6-9 are associated with the action and maintenance stages. Process 10 has an unclear relationship to the stages.

Another model of behavioural change based on stages is the precaution adoption process model (PAPM) (Prochaska et al., 2015). This model proposes 7 stages, similar to the transtheoretical model; however, the stages are 1) unaware of issue; 2) unengaged by issue; 3) undecided about acting; 4) decided not to act or 5) decided to act; 6) acting and 7) maintenance (Prochaska et al., 2015). From stage 1 to stage 2, media messages about the hazard and precaution are likely to factor into the transition between stages. From stage 2 to 3, factors that will influence progression between stages include media messages, communication with significant others and personal experience with the hazard. From stage 3 to either 4 or 5, factors that influence progression between stages include beliefs about the likelihood and severity of the hazard, beliefs about personal susceptibility, beliefs about precaution effectiveness and difficulties, behaviours and recommendations of others, social norms and fear and worry. From stage 5 to 6, factors that influence the progression include, time effort and resources required, detailed information on how to act, reminders and cues to action and assistance.

The difference between the TTM and the PAPM are that the PAPM focuses on mental states whereas the TTM focuses on time periods until action (Prochaska et al., 2015). Other models of behaviour change such as the health belief model, the theory of reasoned action, or the protection motivation theory have been suggested to focus on factors that influence the decision-making process that occurs at stage 3 of the PAPM when individuals are undecided about acting and can choose to either act or not act (Prochaska et al., 2015).

To successfully promote behavioural change, researchers suggest that interventions must be tailored to the individuals' stage of change and should address different things depending on which stage they are at (Prochaska et al., 2015). For example, in the PAPM, those in stages of inaction (stages 1-4) should be provided basic information about the hazard and recommended precautions, individualized messages from close relationships, information and messages that are personally relevant to the individual, and awareness of others making decisions on behavioural change (Prochaska et al., 2015). For those in the action stages (stages 5-7), information should be provided on specific skills and resources needed to support efforts for behaviour change and removing barriers to action (Prochaska et al., 2015). Short-term interventions should not overlook stage progression as a measure of success even if there is limited resulting behavioural change, especially for difficult to change behaviours (Prochaska et al., 2015).

According to protection motivation theory, individual's motivations to protect themselves from hazard depend on the severity of risks, susceptibility to risks, self-efficacy at performing the precautious behaviour and response efficacy of the precautious behaviour (Pechmann et al., 2003). Therefore, to promote a health behaviour, messages or information must target the individuals' appraisal of the threat or the coping response (health behaviour).

In the health belief model, behaviours are influenced by both cues to action and individual beliefs (Champion and Skinner, 2008). Individual beliefs include perceived susceptibility to and severity of the risk that inform the perceived threat, as well as the perceived barriers and benefits of the behaviour, and perceived self-efficacy of in one's ability to act (Champion and Skinner, 2008). These beliefs in turn are also modified by individual factors, such as age, gender, ethnicity, socioeconomics, knowledge, and personality. The individual beliefs similarly center around two major categories, threat appraisal and health behaviour appraisal. To apply these principles in a targeted health promotion campaign, one should provide information to target the individual beliefs. For example, perceived susceptibility could be addressed by personalizing the risk message based on personality or behaviour and defining populations at risk and risk levels, and perceived severity could be addressed by describing consequences of risks and conditions. Perceived benefits and barriers could be addressed by defining the action, when to take the action, how to do it and where to do it, the benefits of the behaviour, correcting misinformation, and providing incentives, reassurance, and assistance for the behaviour. Cues to action and self-efficacy could be addressed by promoting awareness, setting goals, and providing how-to information, training and guidance, verbal reinforcement, demonstrations, reminders, and refreshers (Champion and Skinner, 2008).

To prevent MSDs, researchers encourage ergonomic interventions to draw from the health promotion and behavioural change models and implement stage-matched interventions to increase the probability of success (Whysall et al., 2007; Haslam, 2002). Within the construction sector, mean rankings revealed that workers were more often in earlier stages of change compared to other industries (Whysall et al., 2007). It was also found that most construction workers had little concern for risks associated with their trade (Whysall et al., 2007). Researchers proposed that organizational culture may have a greater influence on worker stage of change, independent of employer interventions (Whysall et al., 2007). With respect to targeting ergonomic interventions, there are three important elements to support health behaviour changes: building and maintaining confidence and motivation for change, education and understanding risks, and training skills and techniques (Haslam, 2002).

2.8 Discussion and Conclusions

To date, MMH training has had little success in reducing pain or rates of MSDs; however, there is some evidence that training can reduce exposure to MSD risks when based on expert work strategies. Expert workers use techniques that are both safer and more productive. Practice reinforcement, and customization are essential to MMH training. This review outlines best principles for effective training based on motor learning, adult learning, and models of health behaviour change from the literature. These principles can be implemented into a training program within the masonry sector to target lifting techniques and reduce physical exposures.

Since training often fails to be transferred to the work environment, it is critical to train workers in an occupational context and during occupational tasks. Many trades in the construction industry, such as masonry, have the educational infrastructure to provide safety and ergonomic training concurrent with apprenticeship training. Proper movement techniques and behaviours can be taught concurrently with technical skills, in ways that have direct relevance to the technical skills they are learning. This also has the advantages of teaching good movement strategies at the beginning of one's career, such that they do not have to change their behaviours later and there are no former poor behaviours to which one may revert. Younger students may also be more receptive to new strategies since they have not yet been socialized into certain behaviours within the construction culture; therefore there may be a lower resistance to change.

Research reports that force, repetition, duration, posture, and vibration are all key biomechanical risk factors for the development of injury (Kumar, 2001). In masonry, among the tasks included within the scope of this thesis, vibration is not a concern. Similarly, while there is high repetition in masonry, which relates to fatigue and cumulative outcomes, fatigue is also outside the scope of our research.

Chapter 3
Development of Quantitative Postural Assessment Criteria[1]

3.1 Introduction

This chapter focuses on (1) analyzing the movements of novice, apprentice, and expert masons to characterise postural characteristics of inexpert and expert techniques; (2) translating these findings into recommendations for best lifting practices to reduce exposure to MSD risks and (3) reviewing the literature and characterisation of inexpert and expert techniques to develop quantitative postural assessment criteria for use in the enhanced training tool. For the enhanced tool to identify at-risk postures and make recommendations, undesirable postures must be quantified. We have chosen to establish thresholds as decision criteria within the enhanced training tool.

This chapter presents an overview of the findings from an in-depth investigation into expert masonry techniques. First, postural thresholds and guidelines in the literature are reviewed and summarized. Novice, apprentice, and expert masons' kinematics are analyzed for a standard wall build and the key markers of these techniques, such as trunk flexion and twisting are translated into thresholds and recommendations for an enhanced apprentice training tool. The tool makes use of findings from the movement analysis to provide lifting recommendations. Masonry movement techniques refers to the kinematics and postures that the expert journeymen adopt while working.

Many studies have researched the links between extreme or awkward postures while working and MSD risk. To establish postural thresholds, research from the literature on the link between joint angles and MSD risk were reviewed. Furthermore, many onsite observational postural risk assessment tools already employ the use of joint angle thresholds. Therefore, this review included experimental or epidemiological studies, already established guidelines or suggested thresholds and thresholds used in ergonomic assessment tool. These findings can then be compared with findings from actual practice to establish threshold values. This literature review was informally structured and did not implement a specific review methodology.

3.1.1 Epidemiological Terminology

With respect to epidemiological studies, the amount of risk associated with joint angles or postures are often described using several different measures, including incidence, prevalence, odds ratios, rate ratio and hazard ratios. An understanding of these terms is necessary to contextualize the risk associated with postural thresholds in the following sections; therefore, a description of the terminology is provided.

- **Incidence:** Rate of new cases in a period.
- **Prevalence:** Number of current cases in a population at a given time.

[1] Part of this chapter is adapted from Ryu, J., **McFarland, T.**, Haas, C., and Abdel-Rahman, E. (2021). Automatic Clustering of Proper Working Posture. Manuscript in preparation.

- **Odds Ratio (OR):** the probability of an event occurring in a group compared with the probability that the event does not occur (Stare and Maucort-Boulch, 2016).
- **Rate Ratio (RR):** ratio of the incidence rate of exposed groups compared with unexposed groups (LaMorte, 2018).
- **Hazard Ratio (HR):** ratio of the probability of the event occurring in the exposed group compared to a control group or the "the ratio of (risk of outcome in one group)/(risk of outcome in another group), occurring at a given interval of time" (Brody, 2016).

3.1.2 Neck

Association between physical exposures and shoulder and neck MSDs include manual materials handling such as lifting, carrying, and pushing or pulling, vibration (shoulder), repetition, twisting and bending of the trunk, and working in static or awkward postures (Mayer et al., 2012; Bernard and Putz-Anderson, 1997). Postural exposures at the neck associated with pain or MSD risk are outlined in Table 1.

Table 1: Postural Exposures at the Neck Associated with Pain or MSD Risk at the Neck/Shoulders

Posture	Exposure	Study	
Flexion	Flexion > 15°	Ohisson et al. (1995)	E
	Flexion > 20° for > 66% of working time	Andersen et al. (2003)	E
	Flexion > 56° (OR = 4.9)	Hünting and Grandjean (1981)	E
	Flexion > 20°	RULA (McAtamney and Corlett, 1993)	A
	Flexion 20° - 45° (Discomfort score 3x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Flexion > 45° (Discomfort score 5x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Flexion > 40°	EN 1005-4 (CEN, 2005)	G
	Flexion > 25° (Moderate/High)	ISO-11226. (2000)	G
		Karwowski (2005)	G
Twist	Twist > 0°	RULA (McAtamney and Corlett, 1993)	A
	Twist 30° - 60° (Discomfort score 2x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Twist > 60° (Discomfort score 8x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Twist > 45°	EN 1005-4 (CEN, 2005)	G
		Delleman and Dul (2007)	G
	Twist > 0° (Moderate/High)	ISO-11226. (2000)	G
		Karwowski (2005)	G
Extension	Extension > 0°	RULA (McAtamney and Corlett, 1993)	A
	Extension 30° - 60° (Discomfort score 4x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Extension > 60° (Discomfort score 9x neutral)		

	Extension > 0° (Moderate/High)	ISO-11226. (2000)	G
		Karwowski (2005)	G
Side Bend	Side bend 30° - 45° (Discomfort score 2x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Side bend > 45° (Discomfort score 7x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Side bend > 10°	EN 1005-4 (CEN, 2005)	G
	Side bend > 0° (Moderate/High)	ISO-11226. (2000)	G
		Karwowski (2005)	G

E = Experimental or epidemiological studies
G = Guidelines or suggested thresholds
A = Ergonomic assessment tool category for increased risk

3.1.3 Shoulders

Occupational risk factors associated with MSDs of the shoulder include repetition, lack of rest, holding a load or handheld tools, working overhead or above shoulder height and working in static or awkward postures (postures with shoulder flexion or abduction angles greater than 60°) (Grieve and Dickerson, 2008; Bernard and Putz-Anderson, 1997; Punnett et al., 2000; Sommerich et al., 1993). The shoulder joint is incredibly complex and as such, there no established thresholds and the amount of elevation associated with risk is disputed in the literature (Grieve and Dickerson, 2008). However, occupational tasks that require shoulder flexion ≥ 45° for 15% of the time or greater, shoulder flexion or abduction > 60°, especially for 10% or greater of the cycle time, or the hands above shoulder height, are associated with higher risk of shoulder MSDs (Bernard and Putz-Anderson, 1997; Grieve and Dickerson, 2008; Miranda et al., 2005; Punnett et al., 2000; Svendsen et al., 2004a; Svendsen et al., 2004b; Van Rijn et al., 2010). Postural exposures at the shoulder associated with pain or MSD risk are outlined in Table 2.

Table 2: Postural Exposures at the Shoulders Associated with Pain or MSD Risk

Posture	Exposure	Study	
Flexion	Flexion > 60°	Bernard and Putz-Anderson (1997)	E
	Hands at or above shoulder height (OR = 10.6, 95% CI: 2.3-54.9)	Bernard and Putz-Anderson (1997)	E
	Hands above shoulder level ≥ 1 hour/day	Miranda et al. (2005)	E
	Flexion > 90°, especially ≥ 10% of the cycle time (Left shoulder OR = 3.2, 95% CI: 1.5-6.5; Right shoulder OR = 2.3, 95% CI: 1.2-4.8)	Punnett et al. (2000)	E
	Flexion > 90°	Svendsen et al. (2004a; 2004b)	E
	Flexion > 45° for ≥ 15% of time (OR = 2.3)	Van Rijn et al. (2010)	E
	Hand above shoulder level ≥ 1 hour/day	Van Rijn et al. (2010)	E
	Flexion > 60° (OR = 4.2, 95% CI: 1.35-13.2)	Ohisson et al. (1995)	E
	Flexion ≥ 60° ≥ 1 h/day	Van der Molen et al. (2018)	E
	Flexion between 20° - 45° (low risk)	RULA (McAtamney and Corlett, 1993)	A
	Flexion between 45° - 90° (moderate risk)	RULA (McAtamney and Corlett, 1993)	A

	Flexion > 90° (high risk)	RULA (McAtamney and Corlett, 1993)	A
	Flexion 90° - 150° (Discomfort score 6x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Flexion > 150° (Discomfort score 11x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Exposure limit of 43.2 mins/day for flexion > 30°	Coenen et al. (2016)	G
	Exposure limit of 0.6 min/day for maximal continuous duration of flexion > 30°	Coenen et al. (2016)	G
	Flexion > 60°	EN 1005-4 (CEN, 2005)	G
	Flexion between 20° - 60° (Moderate)	ISO-11226. (2000)	G
	Flexion > 60° (High)	Karwowski (2005)	
Abduction	Abduction > 90°, especially ≥ 10% of the cycle time (Left shoulder OR = 3.2, 95% CI: 1.5-6.5; Right shoulder OR = 2.3, 95% CI: 1.2-4.8)	Punnett et al. (2000)	E
	Abduction > 60°	Bernard and Putz-Anderson (1997)	E
	Abduction > 45°	Sommerich et al. (1993)	E
	Abduction > 60°	Ohisson et al. (1995)	E
	Abduction 30° - 90° (Discomfort score 3x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Abduction > 90° (Discomfort score 7x neutral)	LUBA (Kee and Karwowski, 2001)	A
Extension	Extension 20° - 45° (Discomfort score 3x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Extension 45° - 60° (Discomfort score 6x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Extension > 60° (Discomfort score 10x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Extension > 20° (low risk)	RULA (McAtamney and Corlett, 1993)	G
	Extension > 0°	EN 1005-4 (CEN, 2005)	G
	Extension > 0° (Moderate/high)	ISO-11226. (2000) Karwowski (2005)	G

E = Experimental or epidemiological studies
G = Guidelines or suggested thresholds
A = Ergonomic assessment tool category for increased risk

3.1.4 Elbows

There is strong evidence supporting an association with forceful exertions and a combination of risk factors (e.g., force and postures or repetition) and epicondylitis, which can be a concern in masonry (Bernard and Putz-Anderson, 1997). Indeed, manual handling jobs, such as in construction, are noted to have higher incidence rates of elbow tendonitis (Werner et al., 2005). Several studies provide further evidence that combinations of repetitive bending and straightening the elbow, non-neutral postures and high physical exertions are associated with greater risk of epicondylitis (Haahr and Andersen, 2003; Shiri et al., 2006; Herquelot et al., 2013; Walker-Bone et al., 2012; Werner et al., 2005; Seidel et al., 2019). Elbow flexion, extension or extreme wrist bending for greater than 2 hours a day with increased physical exertion was noted as a risk factor; however, the degree of elbow flexion/extension was not specified (Herquelot et al., 2013). A more recent systematic review of physical exposures found significant associations between overhead work, hand movements, forearm and elbow movements, non-neutral postures, posture and repetition, and posture and force with specific disorders at the elbow (lateral and medial epicondylitis and ulnar neuropathy; Seidel et al., 2019). Postural exposures at the elbows associated with pain or MSD risk are outlined in Table 3.

Despite insufficient evidence, patients with ulnar neuropathies were recommended by Hegmann et al. (2012) to avoid hyperflexed postures (>90°) at work, noting that these postures appear to "prominently produce the symptoms". Reducing exposure to these postures is considered a simple intervention with low invasiveness and limited adverse consequences, which could be costly if no accommodation is otherwise adopted (Hegmann et al., 2012). Furthermore, ergonomics training is considered beneficial and is "recommended in moderate or high-risk manufacturing settings" despite lacking evidence (Hegmann et al., 2012). For example, for individuals with lateral or medial epicondylalgia, lifting with the palm face up may reduce stress on the lateral aspect of the elbow whereas lifting with the palm face down may reduce stress medially (Hegmann et al., 2012).

Table 3: Postural Exposures at the Elbows Associated with Pain or MSD Risk

Posture	Exposure	Study	
Flexion	Flexion > 100° ≥ 2 hours/day	Seidel et al. (2019)	E
	(OR = 1.82, 95% CI: 1.15-2.89)	Svendsen et al. (2012)	E
	Flexion 0° - 60° or > 100°	RULA (McAtamney and Corlett, 1993)	A
	Flexion 45° - 120° (Discomfort score 3x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Flexion > 120° (Discomfort score 5x neutral)	LUBA (Kee and Karwowski, 2001)	A
Rotation	≥ near maximal pronation/supination 100° ≥ 2 hours/day	Seidel et al. (2019)	A
	(OR = 1.82, 95% CI: 1.15-2.89)	Svendsen et al. (2012)	A
	Forearm rotation ≥ 45° for ≥ 45% time and duty cycle ≥ 10% of time	Seidel et al. (2019)	A
		Fan et al. (2014)	A
	(OR = 3.10, 95% CI: 1.05-9.15)		
	Forearm pronation ≥ 45° for ≥ 40% time and duty cycle ≥ 10% of time	Seidel et al. (2019)	A
		Fan et al. (2014)	A
	(HR = 2.25, 95% CI: 1.09-4.66)		
	Forearm supination ≥ 45° for < 5% time and lifting (≥ 4.5 kg) ≥ 3% of time	Seidel et al. (2019)	A
		Fan et al. (2014)	A
	(HR = 2.09, 95% CI: 1.02-4.27)		
	Forearm supination ≥ 45° for < 5% time and any power grip (≥ 44.1 N)	Seidel et al. (2019)	A
		Fan et al. (2014)	A
	(HR = 2.86; 95% CI: 1.41-5.82)		
	Forearm rotation ≥ 45° for ≥ 45% time and any power grip (≥ 44.1 N)	Seidel et al. (2019)	A
		Fan et al. (2014)	A
	(HR = 2.83, 95% CI: 1.16-6.90)		

	Forearm pronation ≥ 45° for ≥ 40% time and any power grip (≥ 44.1 N) (HR = 2.80, 95% CI: 1.35-5.77)	Seidel et al. (2019) Fan et al. (2014)	A A
	Forearm pronation ≥ 45° for ≥ 40% time and lifting (≥ 4.5 kg) ≥ 3% of time (HR = 2.50; 95% CI: 1.19-5.24)	Seidel et al. (2019) Fan et al. (2014)	A A
	Forearm supination ≥ 45° for ≥ 5% time (OR = 2.25, 95% CI: 1.13-4.50)	Seidel et al. (2019) Fan et al. (2014)	A A
	Forearm supination ≥ 45° and forceful lifting (≥ 4.5 kg) in [% time] (OR = 3.65, 95% CI:1.47-9.07)	Seidel et al. (2019) Fan et al. (2014)	A A
	Forearm supination ≥ 45° ≥ 5% (duty cycle) and forceful lifting (≥ 4.5 kg) > 0% of time (OR = 2.98, 95% CI:1.18-7.55)	Seidel et al. (2019) Fan et al. (2014)	A A

HR = Hazard ratio
OR = Odds ratio
E = Experimental or epidemiological studies
G = Guidelines or suggested thresholds
A = Ergonomic assessment tool category for increased risk

3.1.5 Wrists

Risks for MSDs at the wrist include highly repetitive work, forceful exertions, vibrations, and a combination of factors including posture; this is especially important considering wrist postures during masonry is frequently under load and repetitive (Bernard and Putz-Anderson, 1997). In epidemiological studies, wrist posture has been difficult to analyze due to the variability of wrist postures between workers and jobs, as well as the influence of height on posture in the workplace (Bernard and Putz-Anderson, 1997). Pressures of 30 mmHg or greater in the carpal tunnel, even for brief exposure periods, are associated with negative physiological effects (e.g., hand paresthesia, slow nerve conduction; McGorry et al., 2014). Wrist extension up to 16° not associated with MSD risk (considered a neutral posture range; Lee and Jung, 2014). Postural exposures at the wrists associated with pain or MSD risk are outlined in Table 4.

Table 4: Postural Exposures at the Wrists Associated with Pain or MSD Risk

Posture	Exposure	Study	
Flexion	Flexion < 35° (low risk)	Weresch and Keir (2018)	E
	Flexion between 35° - 51° (moderate risk)	Weresch and Keir (2018)	E
	Flexion > 51° (high risk)	Weresch and Keir (2018)	E
	Flexion at 45° associated with reduced median nerve cross-sectional area	Loh et al. (2014)	E
	Flexion > 45°	Rempel et al. (1999)	E
	Flexion > 60° associated with risk of shear injury of the sub-synovial connective tissue in the carpal tunnel	Yoshii et al. (2008)	E
	Flexion > 15°	RULA (McAtamney and Corlett, 1993)	A

	Flexion 20° - 60° (Discomfort score 2x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Flexion > 48.6° (95% CI: 37.7°–59.4°)	Keir et al. (2007)	G
	Flexion > 60° (Discomfort score 5x neutral)	LUBA (Kee and Karwowski, 2001)	A
	25th percentile angle associated with carpal tunnel pressure threshold of 30 mmHg		
	Flexion > 37.7°	Keir et al. (2007)	G
	25th percentile angle associated with carpal tunnel pressure threshold of 25 mmHg		
Extension	Extension < 17° (low risk)	Weresch and Keir (2018)	E
	Associated with carpal tunnel pressure thresholds at 20 and 30 mmHg		
	Extension between 17° - 33° (moderate risk)	Weresch and Keir (2018)	E
	Associated with carpal tunnel pressure thresholds at 20 and 30 mmHg		
	Extension > 33° (high risk)	Weresch and Keir (2018)	E
	Associated with carpal tunnel pressure thresholds at 20 and 30 mmHg		
	Extension at 45° associated with reduced median nerve cross-sectional area	Loh et al. (2014)	E
	Extension > 45°	Rempel et al. (1999)	E
	Extension > 45° increased carpal tunnel pressures > 30 mmHg	Rempel et al. (1997)	E
	Extension > 15°	RULA (McAtamney and Corlett, 1993)	A
	Extension 20° - 45° (Discomfort score 2x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Extension > 45° (Discomfort score 7x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Extension > 45° Suggested threshold for risk assessment	Harris-Adamson et al. (2015)	G
	Extension > 32.7° (95% CI: 27.2°–38.1°)	Keir et al. (2007)	G
	25th percentile angle associated with carpal tunnel pressure threshold of 30 mmHg		
	Extension > 26.6°	Keir et al. (2007)	G
	25th percentile angle associated with carpal tunnel pressure threshold of 25 mmHg		
Radial Deviation	Radial deviation < 9° (low risk)	Weresch and Keir (2018)	E
	Radial deviation between 9.4 - 22° (moderate risk)	Weresch and Keir (2018)	E
	Radial deviation > 22° (high risk)	Weresch and Keir (2018)	E
	Radial deviation >20° increased carpal tunnel pressure past 30 mmHg	Keir et al. (1998)	E
	Radial deviation > 0°	RULA (McAtamney and Corlett, 1993)	A
	Radial deviation 10° - 30° (Discomfort score 3x neutral)	LUBA (Kee and Karwowski, 2001)	A

	Radial deviation > 30° (Discomfort score 7x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Radial deviation > 21.8° (95% CI: 14.7°–29.0°) 25th percentile angle associated with carpal tunnel pressure threshold of 30 mmHg	Keir et al. (2007)	G
	Radial deviation > 17.8° 25th percentile angle associated with carpal tunnel pressure threshold of 25 mmHg	Keir et al. (2007)	G
Ulnar Deviation	Ulnar deviation < 6° (low risk)	Weresch and Keir (2018)	E
	Ulnar deviation between 6.4° - 18.7° (moderate risk)	Weresch and Keir (2018)	E
	Ulnar deviation > 18.7° (high risk)	Weresch and Keir (2018)	E
	Ulnar deviation > 20°	Hünting and Grandjean (1981)	E
	Ulnar deviation > 30° increased carpal tunnel pressure past 30 mmHg	Keir et al. (1998)	E
	Ulnar deviation > 0°	RULA (McAtamney and Corlett, 1993)	A
	Ulnar deviation 10° - 20° (Discomfort score 3x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Ulnar deviation > 20° (Discomfort score 6x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Ulnar deviation > 14.5° (95% CI: 9.6°–19.4°) 25th percentile angle associated with carpal tunnel pressure threshold of 30 mmHg	Keir et al. (2007)	G
	Ulnar deviation > 12.1° 25th percentile angle associated with carpal tunnel pressure threshold of 25 mmHg	Keir et al. (2007)	G

E = Experimental or epidemiological studies
G = Guidelines or suggested thresholds
A = Ergonomic assessment tool category for increased risk

3.1.6 Low Back

MSDs at the low back are related to physical work, lifting and high forces, bending and twisting, vibration, and static work postures (Bernard and Putz-Anderson, 1997). Given the prevalence of low back pain, many studies have examined the association between work related demands such as lifting and manual labour and low back disorders. Awkward postures, including bending, and twisting are one of the major concerns when it comes to low back MSDs due to their potential contribution to low back compression forces while handling heavy loads. Postural exposures at the low back associated with pain or MSD risk are outlined in Table 5.

Table 5: Postural Exposures at the Low Back Associated with Pain or MSD Risk

Posture	Exposure	Study	
Flexion	Flexion > 45° Relative risk = 3.18 (95% CI: 1.13 – 9) for 1h and 45 min/week compared to 30 min/week	Jansen et al. (2004)	E
	Flexion between 20° - 45° (mild)	Punnett et al. (1991)	E
	OR = 4.9 (95% CI: 1.4 - 17.4)		
	OR = 4.2 (< 10% of cycle time)		
	OR = 6.1 (≥ 10% of cycle time)		
	Flexion > 45° (severe)	Punnett et al. (1991)	E
	OR = 5.7 (95% CI: 1.6 - 20.4)		
	OR = 4.4 (< 10% of cycle time)		
	OR = 8.9 (≥ 10% of cycle time)		
	Flexion > 60° for > 5% of the working time	Hoogendoorn et al. (2000)	E
	Relative Risk = 1.5 (95% CI: 1.0 - 2.1)		
	Flexion > 45°	Neumann et al. (2001)	E
	% Time flexed > 45° OR = 1.3 (95% CI: 1.1 – 1.8)	Neumann et al. (2001)	E
	Flexion ≥ 30°	Hoogendoorn et al. (2002)	E
	10 - 15% of working time RR = 2.03 (95% CI: 1.19 to 3.40)		
	15 - 20% of working time RR = 2.03 (95% CI: 1.19 to 3.40)		
	> 20% of working time RR = 2.33 (95% CI: 1.32 to 3.97)		
	Flexion ≥ 60° for > 5% of working time	Hoogendoorn et al. (2002)	E
	RR = 2.65 (95% CI: 1.59 to 4.32)		
	Flexion ≥ 30° for > 10% of working time and ≥ 60° for ≤ 5% of working time	Hoogendoorn et al. (2002)	E
	RR = 2.27 (95% CI: 1.45 to 3.52)		
	Flexion between 20° - 60° (moderate risk)	RULA (McAtamney and Corlett, 1993)	A
	Flexion > 60° (high risk)	RULA (McAtamney and Corlett, 1993)	A
	Flexion 60° - 90° (Discomfort score 6x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Flexion > 90° (Discomfort score 12x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Exposure limit of 17.74 postures with flexion > 30°/day	Coenen et al. (2016)	G
	Flexion > 40° for > 30 min/day	Kuiper et al. (2005)	G
	Flexion > 20° for > 2 h/day	Van der Molen et al. (2018)	G
	Frequent bending or twisting > 20° for > 2 h/day OR = 1.68 (95% CI: 1.41 – 2.01; Lötters et al., 2003)	Van der Molen et al. (2018)	G
	Flexion > 60°	EN 1005-4 (CEN, 2005)	G
	Static Postures	ISO-11226. (2000)	G
	Flexion between 20° - 60° (Moderate)	Karwowski (2005)	

	Static Postures	ISO-11226. (2000)	G
	Flexion > 60° (High)	Karwowski (2005)	
	Repetitive Postures	ISO-11226. (2000)	G
	Flexion > 20° > 1 h/day	Karwowski (2005)	
Extension	Extension 10° - 20° (Discomfort score 4x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Extension 20° - 30° (Discomfort score 8x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Extension > 30° (Discomfort score 15x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Extension > 0°	EN 1005-4 (CEN, 2005)	G
	Extension > 0° (Moderate, unless with full trunk support)	ISO-11226. (2000) Karwowski (2005)	G
Twist and Lateral Bend	Twist or side bend > 20° OR = 5.9 (95% CI: 1.6 - 21.4) OR = 6.6 (< 10% of cycle time) OR = 3.8 (≥ 10% of cycle time)	Punnett et al. (1991)	E
	Twist ≥ 30° for 5 – 10% of working time RR = 2.12 (95% CI: 1.45 to 3.07)	Hoogendoorn et al. (2002)	E
	Twist or side bend > 0°	RULA (McAtamney and Corlett, 1993)	A
	Side bend 10° - 20° (Discomfort score 4x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Side bend 20° - 30° (Discomfort score 9x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Side bend > 30° (Discomfort score 13x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Twist 20° - 60° (Discomfort score 3x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Twist > 60° (Discomfort score 10x neutral)	LUBA (Kee and Karwowski, 2001)	A
	Twist > 40° for > 30 min/day	Kuiper et al. (2005)	G
	Twist or side bend > 20° for > 2 h/day	Van der Molen et al. (2018)	G
	Twist or side bend > 10°	EN 1005-4 (CEN, 2005)	G
	Twist or side bend > 0° (Moderate/high)	ISO-11226. (2000) Karwowski (2005)	G

OR = Odds Ratio
RR = Adjusted Rate Ratio of Absences 3 days or longer due to LBP
E = Experimental or epidemiological studies
G = Guidelines or suggested thresholds
A = Ergonomic assessment tool category for increased risk

3.1.7 Knees

Frontal plane knee motion is considered a risky movement behavior and maintenance of proper knee alignment while lifting or squatting is critical to reduce injury risk (Ageberg et al., 2010; Frost et al., 2015). Knee abduction angle and loads are associated with knee injuries and pain e.g. patellofemoral pain and is related to worse function post injury (Ageberg et al., 2010; Cronström et al., 2016; Hewett et al., 2009). This may be due to high ligament stress created by the knee abduction moment, or by increasing the patellofemoral contact pressure (Hewett et al., 2009; Powers, 2003). Both increased knee abduction (valgus) or knee medial to foot position in the frontal plane are deemed inappropriate and at-risk movement patterns (Ageberg et al., 2010; Cronström et al., 2016). Previous studies have reported knee abduction angle as the 2D angle between the thigh and shank in the frontal plane and as the 3D abduction/adduction angle at the knee (Ageberg et al., 2010). Increased knee abduction angles and moments, and decreased knee flexion angles contribute to knee injury risk (Hewett et al., 2012). This is relevant to sports performance where sudden loads are greater; however, the importance of reducing frontal plane knee motion extends into the occupational workforce due to the high and repetitive handling of loads. Previous research shows that there is strong evidence for an association between occupational tasks such as manual handling and prolonged or repeated knee bending (i.e., occupational kneeling or squatting) and knee osteoarthritis (Amin et al., 2008; Coggon et al., 2000; Cooper et al., 1994; D'Souza et al., 2005; Englund, 2010; Palmer, 2012). Cooper et al. (1994) reported that occupational kneeling has an odds ratio of 3.4 (95% CI 1.3-9.1) whereas occupational squatting has an odds ratio of 6.9 (95% CI 1.8-26.4) in individuals whose job requires the respective activity for over 30 minutes a day. Joint malalignment, in addition to increased loading, joint instability, meniscal tear and cruciate ligament injury are among the most important biomechanical factors in the causal chain from occupational exposure and knee OA (Englund, 2010).

Squatting is a fundamental movement pattern and one of the key movement strategies for lifting. Malalignment of the knees during a squatting motion can lead to increased shear and compressive forces on the ligaments, tendons, menisci and cartilage leading to knee dysfunction and pain. Patellofemoral forces during a bodyweight squat alone can be up to 4.6 times bodyweight in compression and 3.5 times bodyweight in shear (Dahlkvist et al., 1982; Kritz et al., 2009). Furthermore, tibiofemoral compression forces were reported up to 367% of the sum of bodyweight and load lifted, and shear values were reported up to 99% of the sum of bodyweight and load lifted (Escamilla and Rafael, 2001). Faulty movement patterns associated with squatting at the knees include medial or lateral knee motion (varus or valgus) in the frontal plane or excessive anterior position of the knees relative to the feet (Kritz et al., 2009). Malalignment of the knees (increased medial or anterior knee excursion) altered joint torques and power and lead to increased ankle and trunk contributions to perform the movement (Slater and Hart, 2016). In the anteriorly misaligned squat, internal knee extension moment increased during 33% to 66% of the squat cycle and knee joint power generation increased during 54% to 70% of the squat cycle, which corresponds with the timing of peak knee flexion in the squat, thereby posing a risk for increased patellofemoral contact forces (Slater and Hart, 2016). Similarly, in a deadlift (another key lifting strategy), knee valgus or varus are considered dangerous and undesired movement patterns (Spencer and Croiss, 2015). Neutral frontal plane knee alignment (knees tracking over the feet) should be maintained during various exercises such as squatting and deadlifting and can also be applied to lifting motions during manual handling.

In a study of 15 healthy individuals with neutral knee alignment during level walking with normal gait, peak abduction angle was -2.1° ± 2.5° and peak adduction angle was 2.4° ± 2.7° (Bennett et al., 2017). Furthermore, mean knee abduction angles at peak contact in a drop vertical jump test was 1.4° in a healthy population, compared with mean knee abduction angles of 9° in athletes who would later injure their anterior cruciate ligament (Hewett et al., 2005).

From these healthy populations we can infer that deviation from the neutral within 1-2° is acceptable but excessive deviation should be avoided.

3.2 Methods

While the in-depth literature review provides a jumping off point to establish joint angle thresholds, it is important to also consider experimental data of masons themselves to determine which undesirable postures warrant feedback via the enhanced tool. A thorough investigation of novice, apprentice and expert mason techniques will provide insight into desired postural characteristics that will form the basis for recommendations and undesirable postural characteristics that will form the basis for the development of thresholds to trigger feedback within the enhanced tool. Section 4.2 reviews the experimental setup methods to collect onsite data from inexpert and expert masons. Sections 4.3-4.5 focus on the analysis of kinematic data from novice, apprentice, and expert masons to discern techniques that lead to reduced MSD risk in experts and techniques that lead to increased MSD in apprentices.

3.2.1 Experimental Set-Up

Participants laid and affixed 45 concrete masonry units (CMUs), weighing 16.6 kg, on top of a prebuilt lead wall (Figure 2). The final wall was 6 courses high, with the participants laying the CMUs from the 2nd course to the 6th course. There were two boards for mortar in between 3 stacks of 16 CMUs (4 rows of 4) spaced approximately 1 meter away from the lead wall. Mixed mortar was continuously supplied to the mortar boards to avoid delays during the experimental data collection. This is a typical task used in masonry skills training courses to represent a standard wall build. Sixty-six masons from vocational training institutions in Ontario, Canada participated in the experiment. 17 of the masons were novices with no prior masonry experience, 19 were first year apprentices, 16 were third year apprentices and 14 were red-seal journeymen with 20 or more years of experience. For a full description of the experimental methodology, please see Ryu et al. (2020a).

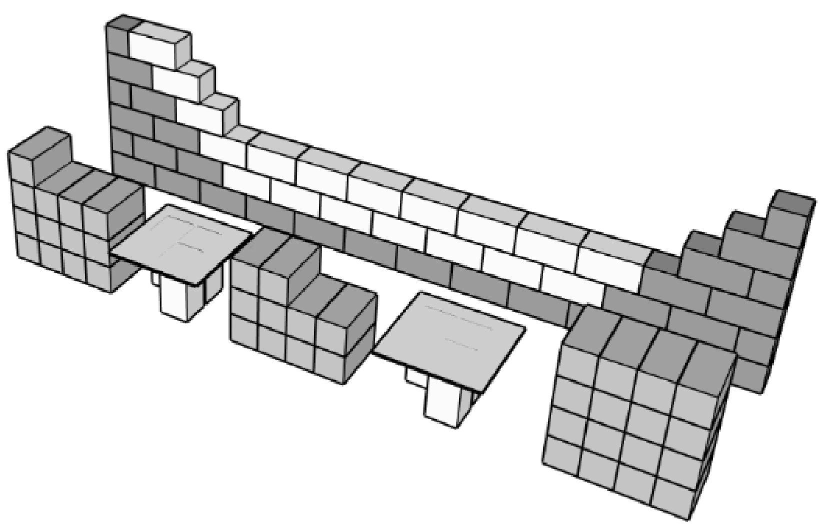


Figure 2: Experimental Set Up of Standard Wall Build

3.2.2 Data Collection

Motion data was captured at 125 Hz using wireless inertial measurement unit (IMU) suits (Figure 3) from MVN Awinda (Xsens, Netherlands) and Perception Neuron (Noitom, USA). Each suit had 17 IMU sensors attached to the head, back, shoulders, upper and lower arms and legs, hands, and feet. Each participant performed calibration poses (T-pose, A-pose, S-pose) prior to data collection to determine segment lengths and ensure alignment between the body and the sensors. Both IMU suits have been previously compared to optoelectronic motion capture systems and found to have sufficient accuracy. For MVN Awinda, the technological error stayed under 5 degrees root mean square error (RMSE) during handling tasks (Robert-Lachaine et al., 2017) while perception Neuron had an average technological error of 5.8 and 4.9 degrees for RMSE for frontal and transverse axes and 10.5 degrees about the longitudinal axis (Robert-Lachaine et al., 2020). Nevertheless, for many joints and axes the root mean square stayed under 5 degrees (Robert-Lachaine et al., 2020).

Figure 3: Inertial Measurement Unit Suits

Data from the IMU sensors were processed by MVN Studio and Axis Neuron software, which reconstructed skeletal models. The IMU software uses a proprietary algorithm and filters to reduce sensor drift and noise. Body segment location and orientation data was then exported as .BVH files. MATLAB was used to calculate joint angles from the coordinate data according to International Society of Biomechanics guidelines (14-16; Wu et al., 2002; Wu et al., 2005; Grood and Suntay, 1983). Measured outcomes included 25 joint angles (1-3 angles/joint, 12 joints), vertical, anterior, and lateral CMU carrying distances and lateral and anterior/posterior stance distance. Vertical carrying distance was defined as the vertical distance from the hip to the hand carrying the CMU along the Y axis (upwards/downwards from the pelvis). The anterior carrying distance was defined as the anterior distance from the hip to the hand carrying the CMU along the X-axis (forward/backward from the pelvis). Lateral carrying distance was defined as the anterior distance from the hip to the hand carrying the CMU along the Z-axis (right side/left side from the pelvis). Lateral stance distance was calculated as the anterior distance from the left ankle to the right ankle along the Z-axis based on the position of the pelvis (right side/left side). And the anterior/posterior (A/P) stance distance was calculated as the anterior distance from the left ankle to the right ankle along the X-axis based on the position of the pelvis (forward/backward).

IMU data was recorded continuously and later segmented visually based on an accompanying recorded video of the tasks. The data was segmented for each individual lift of a CMU, from the moment the participant picked up the CMU to the moment the CMU was placed on the wall. Each lift was then labelled by course number. After segmentation, there were a total of 45 lifts for each participant. The BVH files define body segments as local rotations and transformations from the hip (the root body joint) and the global positions of the joints are then computed from transformation matrices.

3.2.3 Static Model

The kinematic and kinetic model employed a 15-segment multibody system (head, pelvis, torso, left and right upper arms, forearms, hands, thighs, shanks, and feet) with the pelvis as the root segment, with the joints connecting two segments. The joints considered were the lumbar joint (L5/S1), the neck, the right and left shoulder, elbow, wrist, hip, knee, and ankle joints. The trunk was defined as a single rigid segment relative to the pelvis segment. The external CMU weights were added for each lift and categorized as a single hand lift, double hand lift, or a mixed lift. The weights were added based on known load values for the CMUs lifted and the accompanying video recording. The full weight of the CMU was allocated to a single hand for single handed lifts. The CMU weight was split evenly for double handed lifts. For mixed lifts the weight was allocated to either a single hand or double hand throughout the lift according to the accompanying video.

For the calculation of static loads, the BVH files were converted into joint location files and inputted into the software program 3DSSPP (3D Static Strength Prediction Program; The Center for Ergonomics at the University of Michigan) to estimate the compression forces on the lumbar joint (L4/L5) and the joint moments at the shoulders, elbows, wrists, hips, knees, and ankles. Static joint loads were used, which may underestimate the total loads; however, static analysis remains a common practice in ergonomic analysis. Previous research indicates that there is a difference of approximately 4-14 relative RMSE between a dynamic model and the static model employed in this study (Diraneyye, 2019).

The model used in 3DSSPP is a top-down model that calculates the joint moments as singular moments. However, at the L4/L5 joint, contact forces (anterior-posterior shear, lateral shear and compression forces) are computed using a 10-muscle model and double optimization techniques (5 muscles on the left and right sides). For a full description of the kinetic model, please see 3DSSPP program manual (The Center for Ergonomics at the University of Michigan).

3.2.4 Data Analysis

The collected motion data was used to analyze and compare expert and inexpert movement strategies while building a standard wall. The analysis of each groups' respective techniques indicated potential areas for improvement in inexpert participants' work techniques and safer and more productive expert work techniques. Three analysis methods were used to gain insight into the movement strategies of the different groups of masons:

1. predictor screening
2. statistical analysis

3. k-means clustering

Predictor screening was first used to narrow down the analysis from all available kinematic variables to a smaller set with the greatest influence on key joints for the subsequent statistical analysis. Predictor screening identifies the major aspects of technique that contributed to high forces or moments at the joints of concern: the low back and the shoulder. Furthermore, the predictor screening cements the link between the kinematic variables analysed in the statistical analysis and the high-risk outcomes (high joint forces and moments).

Statistical analysis of the full kinematic dataset identified significant effects of experience on the kinematic variables such as joint angles, carrying distance and stance distance, as well as significant interaction effects between experience group and course height. However, discussion of the results was focused on those factors pointed out by predictor screening. Statistical analysis was also conducted on the whole-body kinematic variables at instances of peak joint loads where difference in technique between inexpert and expert masons were likely to be most apparent. The statistical analysis provided a rigorous framework by which to identify differences between kinematic variables that could be attributed to differences between masons' level of experience.

Lastly, a machine learning method, k-means clustering, was used to categorize full postures into apprentice dominated and expert dominated clusters. This provides another layer to the analysis by investigating postures of the entire body rather than single kinematic elements and revealing how postures might differ between experience groups and why individual kinematic variables identified in predictor screening and statistical analysis had an impact on critical joint loads. The factors investigated in each analytical method are described in Table 6 and the relationship among all of the variables is depicted in Figure 4.

Table 6: Relationships among Variables in Each Analytical Method

Method	**Predictor Variables**	**Outcome Variables**
Predictor Screening	Kinematic variables • Joint angles • CMU carrying distance • Stance distance Experience group Course height	Low back loads Shoulder moments
	Independent Variables	**Dependent Variables**
Statistical Analysis	Experience group Interaction between experience group and course height	Kinematic variables • Joint angles • CMU carrying distance • Stance distance
	Categorization Criteria	**Variables**
K-means Clustering	Percentage of apprentices and experts Phase of lift Type of posture	Whole-body postures

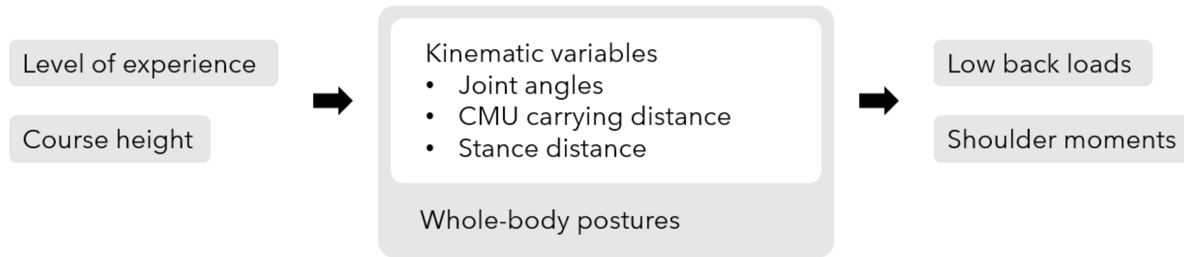


Figure 4: Influence Diagram Depicting Impact of Variables on Outcomes

3.3 Predictor Screening

Due to the large number of joint angles and postural characteristics calculated from the motion data, predictor screening was used to identify which postural variables were associated with high joint loads at the back and shoulder. Predictor screening was conducted in JMP (SAS Institute, USA) which employed bootstrap forest partitioning (Hastie et al., 2009) to determine the contribution of each element to the evaluated outcome. The forces and moments at the low back and shoulder were chosen due to the high rates of injury and increased injury risk at these areas in masonry. The top contributions were analyzed by experience group to see if there were differences across the experience groups based on technique. For the predictor screening model, all 30 kinematic variables including joint angles about each axis, carrying distances, stance distances, as well as experience level and course height were input into the model as potential predictors for the loads at the low back and shoulder. The data was not reduced prior to input. Therefore, the data for each point in time was retained and input into the model, resulting in an analysis of a total of 1,592,801 frames equivalent to approximately 3.5 hours of data. The analyses were performed Oct 19th, 2020.

The top 10 contributors accounted for 78.8-86.7% of the forces and moments, which shows that the predicted contributors were adequate in describing most of the outcome variables. Additionally, only the first 4-5 ranking postural variables contributed greater or equal to 5%, as predictors of the outcome, indicating that the outcomes were largely influenced by only a few postural variables. Therefore, training should target these postural variables first to have the greatest potential for impact. While the predictor screening analysis lists the different contributions of the postural variables to predict the joint loads, it is important that we analyze the values of the postural variables themselves into account as well to better determine the trends and provide context for this data. The full results of the predictor screening analysis can be found in Appendix C.

The top ten kinematic contributors accounted for 86.7% of L4/L5 compression; however, only the top four were closely correlated with contributions larger than 5% (Figure 5). The highest contributor is torso flexion with approximately 25%. This is followed by characteristics of the CMU carrying technique, namely the vertical and anterior carrying distance (16.3% and 12.2% respectively), and then neck flexion (12%). All these factors impact the anterior moment arm and consequently the anterior moment about the lumbar joint, which increases manual handling risk. For L4/L5 anterior/posterior shear forces, the top ten kinematic contributors accounted for 78.8% of the forces; however, only the top six had contributions greater than 5% (Figure 5). The greatest contributor was, again, torso flexion (18.7%) followed by vertical carrying distance (15.6%), A/P stance distance (11.4%), left hip flexion (7.4%), neck flexion (5.7%), and experience group (5%). It is unsurprising that torso flexion has the largest contribution towards anterior/posterior shear forces at the lumbar spine. For L4/L5 lateral shear forces, the top ten contributors accounted for ~81.5.5% of the forces; however, only the top 4 postural variables had contributions greater than 5% (Figure 5). Torso flexion was once again the highest contributor at 25.9%, followed by vertical carrying distance (20.3%) right hip flexion (7.9%) and neck flexion (6.1%). These contributors are similar to the major contributors for L4/L5 compression and anterior/posterior shear as well.

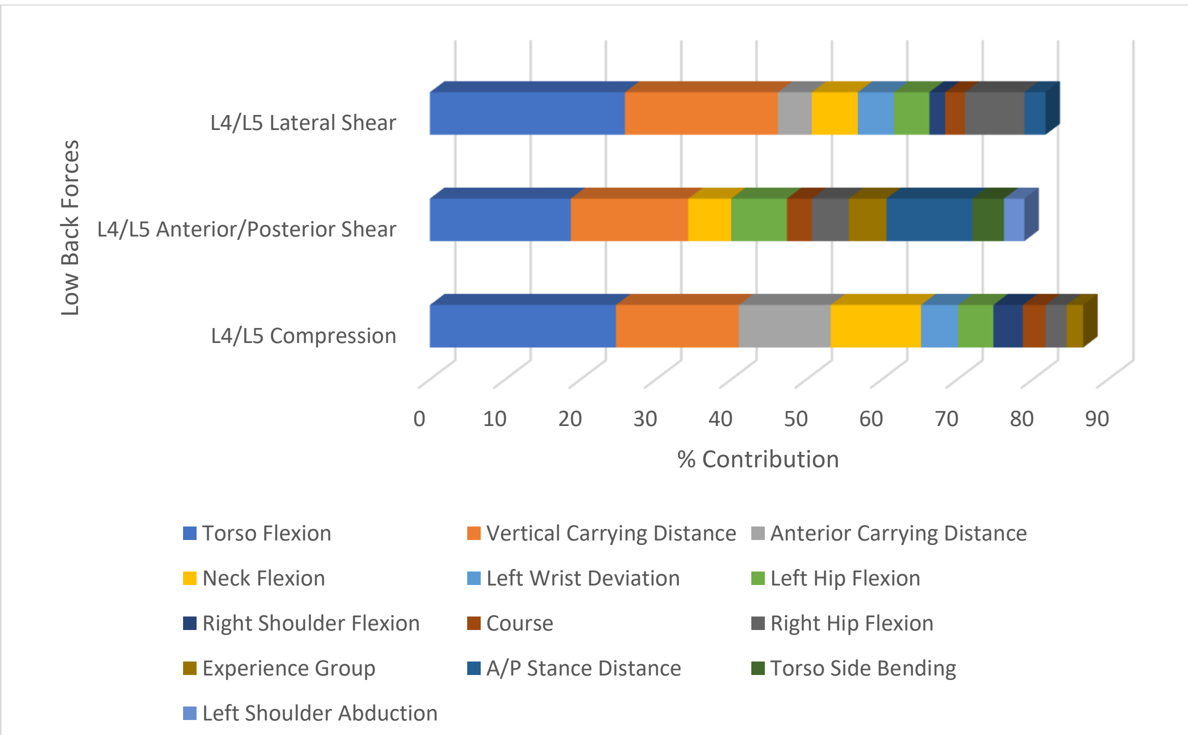


Figure 5: Top Ten Contributors Towards Low Back Forces

The top ten kinematic variables accounted for ~84.7% of the predicted contributions to left shoulder moment (Figure 6). The greatest contribution was from vertical carrying distance (21.9%), then torso flexion (17.7%) and right hip flexion (9%). The subsequent ranking contributors were left shoulder abduction (6.9%), neck flexion (6.4), left hip flexion (5.7%), anterior carrying distance (5.3%) and left shoulder flexion (5.1%). The top 8 ranking variables had contributions above 5%. This is contrary to the other joint loads at the low back in which only a few variables have large contributions. This may indicate that the left shoulder moment is affected to a lower degree by more kinematic variables. At the right shoulder, the top ten kinematic variables accounted for ~81.7% of the predicted contributions to the right shoulder moment (Figure 6). The top 2 ranking contributors were the same as for peak left shoulder moment; however only the top 6 had contributions above 5%. The main contributor was vertical carrying distance (18.5%), followed by torso flexion (18.2%), right shoulder flexion (10%), left hip flexion (8.7%), neck flexion (7.4%) and right hip flexion (6.4%). For peak shoulder moment on both the left and right side, the most important factors contributing to greater loads were the vertical carrying distance and torso flexion, as well as shoulder flexion or abduction on the side of interest, in addition to both neck flexion and hip flexion. Anterior carrying distance also played a small role for the left (5.3%) and right (4.3%) side.

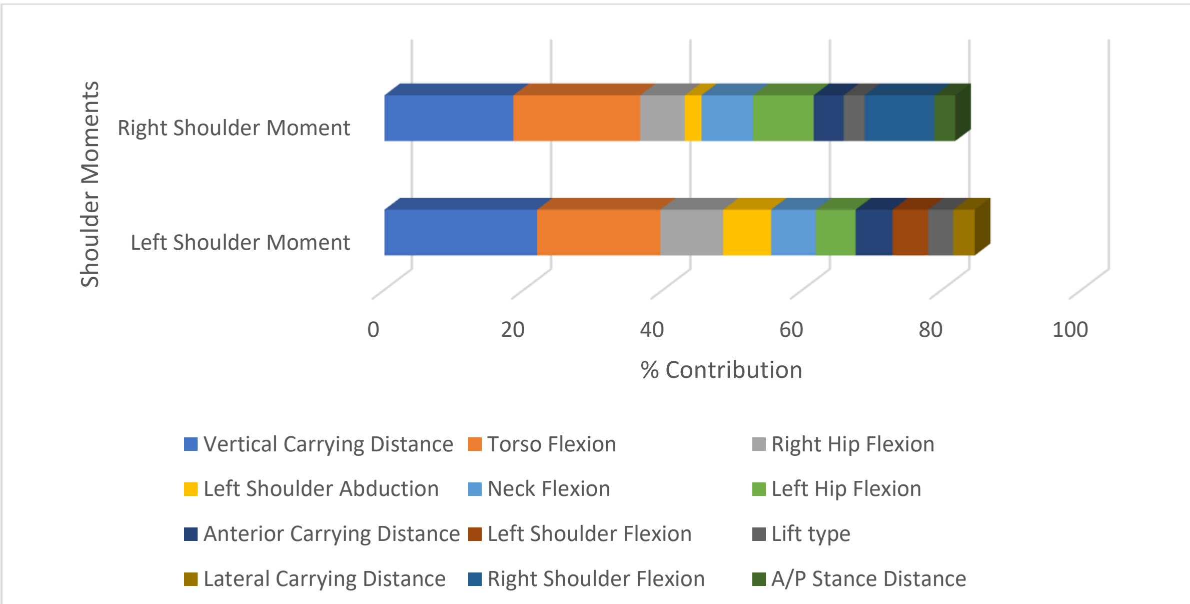


Figure 6: Top Ten Contributors Towards Shoulder Moments

Both experience group and course height had small contributions to the predicted outcomes (1-5%). Course height had marginally larger contributions than experience group for L4/L5 compression, L4/L5 lateral shear, and left shoulder moment, but vice versa for L4/L5 anterior/posterior shear and right shoulder moment. This may indicate that in some cases, task constraints may be a greater concern when it comes to joint forces and moments than other factors such as certain aspects of technique and expertise. In fact, task changes are always the primary recommendation to reduce MSD risk rather than training. However, the contribution of experience group, as one of the top ten contributors for joint forces at the low back demonstrates that experience does play a role in the resulting body loads as well. Additionally, postural variables had higher contributions than course height in many cases, e.g., anterior carrying distance, highlighting the importance of technique in the resulting joint loads and moments. Lift type had small contributions to shoulder moments only (3-3.6%), indicating that lift type did not have a large effect on the low back loads but may have affected shoulder moment. This is due to increased moment at one shoulder in a single-handed lift due to more weight being lifted by a single arm.

The predictor screening results for peak forces/moments by experience group, are included in Appendix C. Among the top ten contributors there were small differences across experience groups. The most noticeable difference was that journeymen, as opposed to all other groups, had vertical carrying distance as the top contribution (18.2%) and torso flexion as the second contributor (14.9%) rather than vice versa. For all other groups, torso flexion contributed 18.2-23.4%. This demonstrates that the degree of torso flexion is a greater factor for L4/L5 compression forces in novice and apprentice masons, whereas it plays a slightly lesser role in journeymen. For all groups except 3rd year apprentices, the next highest-ranking contributors (Ranks 3-6) were various orders of anterior carrying distance, left and right hip flexion and neck flexion. For journeymen the third contributor was anterior carrying distance (11%) followed by neck flexion (5.2) and then left (4.7%) and right (3.3%) hip flexion. For 3rd year apprentices however, the contributors ranking 3-6 were neck flexion (11.1%) followed by anterior carrying distance (8.6%), left wrist deviation (8%) and torso side bending (6.2%). This may indicate that neck flexion, left wrist deviation and torso side bending may be more of a concern contributing to higher L4/L5 compression for 3rd year apprentices. Lateral carrying distance was also implicated in the top ten for journeymen (3.2%) but not for the other groups. This may point to a different carrying strategy by journeymen, but it is unclear from this information alone. These differences indicate that experts have a different carrying technique from the other groups.

Among the top contributors to L4/L5 A/P shear by experience group, torso flexion was the top contributor for L4/L5 A/P shear in novices and apprentices, but the third rank for journeymen. Torso flexion only contributed 8.1% in journeymen compared to 13.2-19% in apprentices and novices. Furthermore, vertical carrying distance wes the top contributor in journeymen (11.2%) but contributed a similar amount to the apprentice groups (11.3-12.5%). This indicates a different carrying technique. A/P stance distance was a large contributor to L4/L5 A/P shear in novices (9.8%), 3rd year apprentices (10.2%) and journeymen (8.1%) but the direction of the relationship is unclear. More information is needed to better characterize this relationship.

Separating the postural contributions by experience group, torso flexion was still the greatest contributor across all groups. However, it was higher for novices and 1st year apprentices (24.1-25.4%) compared to 3rd year apprentices and journeymen (14.5-15.6%). Anterior carrying distance was the 3rd and 4th ranking contributor for journeymen and novices, respectively, but contributed similar amounts (6.8% and 5.8%). On the other hand, the 1st year and 3rd year apprentices had lower contributions of anterior carrying distance (3.4-4.6%). This reinforces the observation that different experience groups have different carrying techniques. Left wrist deviation was one of the top contributors for both 3rd year apprentices (5.1%) and journeymen (6.1%) but played a lesser role for novices and 1st year apprentices. This may be an indicator of asymmetry in the lifting posture. Additionally, neck flexion was a greater contributor to 1st year (6%) and 3rd year (8.4%) apprentices compared to novices (1.4%) and journeymen (4.3%). Lastly, left and/or right hip flexion were among the top-ranking contributors for all groups.

For both mean L4/L5 A/P and lateral shear, neck flexion had greater contributions to the apprentice groups compared to the other groups. Additionally, vertical carrying distance and torso flexion were among the top 4 contributors across all groups and shear directions and among the top 3 in all cases except 1.

For each of the experience groups, the top 2 contributors were the same: vertical carrying distance (16.4-25.4%) and torso flexion (9.7-18.5%). For journeymen, the subsequent highest contributors were left shoulder abduction (9.7%), anterior carrying distance (6.7%) and left shoulder flexion (6%). All are directly mechanically related to left shoulder moment. For the other groups, the subsequent highest contributors were more indirectly related to shoulder moment such as right hip flexion, neck flexion, left hip flexion as well as anterior carrying distance and left shoulder abduction.

In the predictor screening analysis by experience group, all groups had vertical carrying distance, torso flexion and right shoulder flexion among the top 4 contributors. In 3rd year apprentices, left hip flexion was the highest-ranking contributor at (18.7%) whereas in left hip flexion contributed 8.1% and 8.8%, in 1st year apprentices and journeymen, respectively, while in novices right hip flexion contributed 5.4%. Further analysis is needed to contextualize the relationship of hip flexion with shoulder moment among different experience groups.

Overall, the key postural variables that predicted loading at the lower back (> 5%) were torso flexion, vertical carrying distance, anterior carrying distance, neck flexion, A/P stance distance, right and left hip flexion and experience group (A/P shear in particular). The key postural variables predicting at the shoulder (> 5%) were vertical carrying distance, torso flexion, shoulder flexion, hip flexion, anterior carrying distance, neck flexion and shoulder abduction.

Key postural variables affecting loads at the lower back (> 5%):

- Torso flexion
- Vertical carrying distance
- Anterior carrying distance
- Neck flexion
- A/P Stance Distance
- Right and left hip flexion
- Experience group (left wrist deviation)
- Experience group (A/P shear)

Key postural variables affecting loads at the shoulder (> 5%):

- Vertical carrying distance
- Torso flexion
- Shoulder flexion
- Hip flexion
- Anterior carrying distance
- Neck flexion
- Shoulder abduction

The combination of these kinematic variables constitutes the key kinematic variables that will be further analyzed in the next section.

3.4 Statistical Analysis

A statistical analysis was conducted to identify the main effect of experience group and the interaction effect of experience group and course height on the kinematic and kinetic variables. While all 30 kinematic variables were analyzed, the focus of the results within this report was narrowed down based on the previous predictor screening. A mixed effect model was implemented in JMP at a significance level of 0.05. A box cox transformation was used to transform the data prior to analysis due to the long tails in the data. To prepare the data for the box cox transformation, constants were added to the dependent variables, as follows: 200 for the joint angles; 60 for the CMU carrying and stance distances; and 2000 for joint loads. Independent variables included experience group and course height. Participant number was also included as a random effect. Tukey's test was used for post-hoc analysis. The reported means and standard deviations represent the raw data, whereas the significance tests and post-hoc analyses were carried out on the transformed data. Family-wise error was not controlled. The methods used for the statistical analysis were established in consultation with the Statistical Consulting and Collaborative Research Unit at the University of Waterloo.

Two parallel analyses were conducted on the kinematic variables:

1. Full lift analysis
2. Peak frame analysis.

For the full lift analysis (entire task), there was no reduction in data, resulting in a total of 1,592,801 frames equivalent to approximately 3.5 hours of data collection. For the peak frame analysis, the data was reduced to instances of peak low back and shoulder loads for each lift (with a total of 45 lifts) and each participant (for a total of 66 masons). The postures at those instances were analyzed to elicit the highest-risk movement strategies adopted by the different experience groups. The effect of experience on kinematic variables at peak frames is contrasted to the results of the full lift analysis in the results section. The interaction effect of experience and course height at peak frames were omitted due to lack of additional insights.

3.4.1 Effect of Experience and Course Height on Kinematics

For the entire task, there was a significant main effect of experience group as well as a significant interaction effect between experience group and course height on all 30 kinematic variables (Appendix D).

Within experience groups, neck flexion was greatest at courses 3 and 4; neck flexion increased from course 1 to a peak at courses 3 or 4 then decreased at course 5 (Figure 7). Across all courses, 3rd year apprentices had the highest neck flexion compared to all other groups. Experience group had a larger influence on neck posture than course height. The largest variation due to course height was for journeymen (10.6°), while the largest difference due to experience groups was at course 2 between 3rd year apprentices and journeymen (13.0°). Journeymen had the least amount of neck flexion for courses 2-5 and have neck extension at course 1. At course 1 (lowest course), masons may get closer to the ground by bending at the hips or torso, resulting in overall greater low back loads. The effect of neck extension at the lower heights may have reduced additional moment created by the weight of the head. Neck flexion may also be related to the choice of bending strategy: in k-means analysis, in the lay down phase (especially in equally represented bins), the neck was more likely to be flexed in a squatting position, compared to a deadlift, or hinged position, in which neck extension or more neutral neck postures were more common.

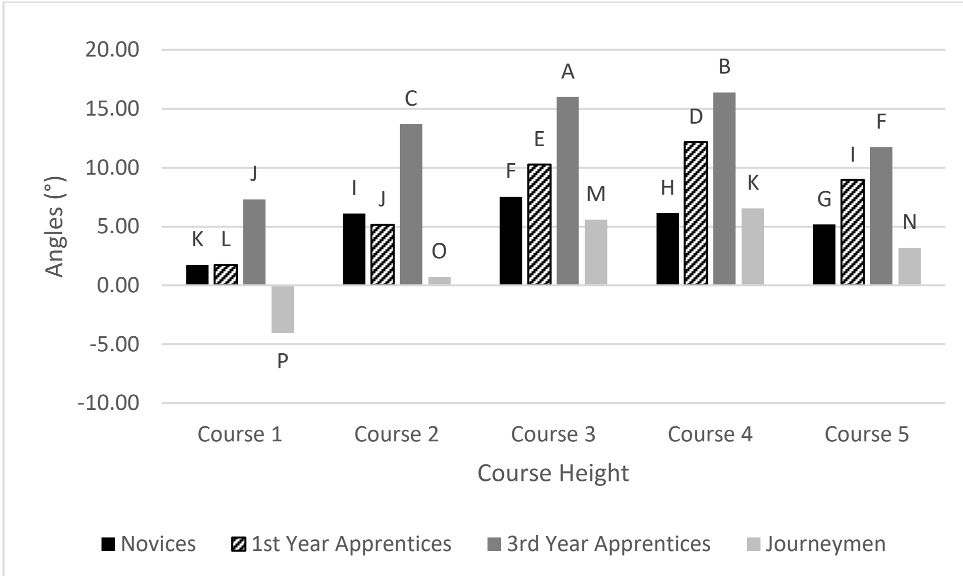


Figure 7: Interaction Effect of Experience Group and Course Height on Mean Neck Flexion

The highest amount of left shoulder flexion within experience groups occurred at course 1 and 5 (the highest and lowest courses), while the least left shoulder flexion occurred at course 3 (Figure 8). For all experience groups, left shoulder flexion decreased from course 1 to 3 then increased from course 3 to 5. All groups experienced the highest left shoulder flexion at course 5 except for novices who had the highest left shoulder flexion at course 1. For courses 1-4, journeymen had significantly higher left shoulder flexion compared to all other groups. This is followed by both apprentice groups for courses 1 and 4. Within course height, the difference between the maximum and minimum shoulder flexion for novices was 9.2°, for 1st year apprentices it was 12.2°, for 3rd year apprentices it was 17.4° and for journeymen the difference was 9.7°. The largest difference between experience groups occurs at course 5, with a difference of 11.6° between 1st year apprentices and novices. Course height had larger impact on differences between max and min shoulder flexion compared to experience. Journeymen had greater left shoulder flexion at each course height and maintained more shoulder flexion throughout the task (smaller range between the courses with highest flexion at courses 1 and 5 and the lowest flexion at the middle course).

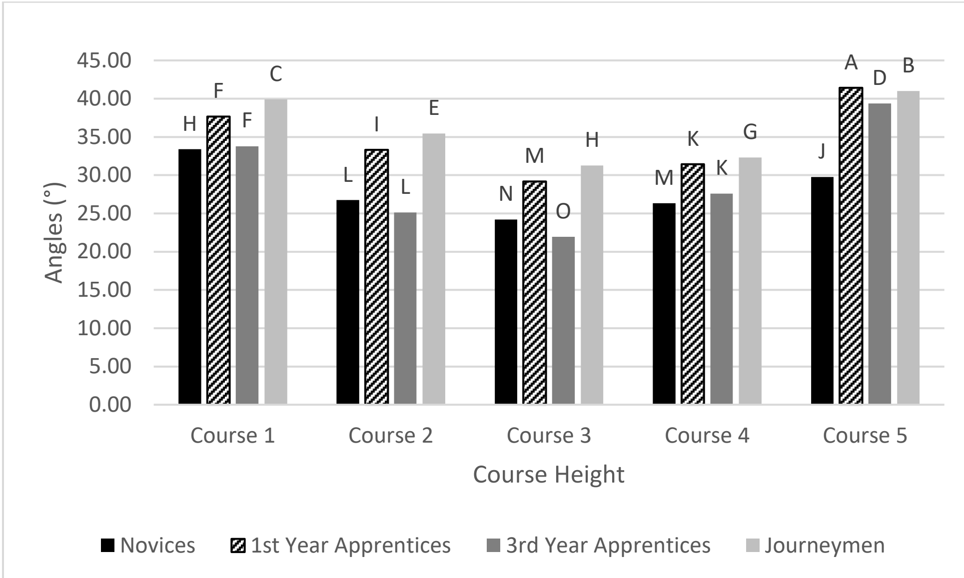


Figure 8: Interaction Effect of Experience Group and Course Height on Mean Left Shoulder Flexion

There were similar and more consistent patterns for right shoulder flexion. At each course height, novices had significantly lower right shoulder flexion compared to all other groups by up to 33.9% (16.0°; Figure 9). At courses 2-5 journeymen had significantly higher right shoulder flexion compared to all other groups. Similar to the left shoulder, the highest amount of right shoulder flexion within experience groups occurred at course 1 and 5 (the highest and lowest courses), while the least right shoulder flexion occurs at course 3. All groups experience the highest right shoulder flexion at course 5 except for novices who have the highest right shoulder flexion at course 1. Within course height, the difference between the maximum and minimum shoulder flexion for novices was 11.2°, for 1st year apprentices it was 11.3°, for 3rd year apprentices it was 15.0° and for journeymen the difference was 16.6°. The largest difference between experience groups occurred at course 5, with a difference of 16.0° between journeymen and novices. Course height has larger impact on differences between max and min shoulder flexion compared to experience. Journeymen had greater right shoulder flexion at most course heights (2-5) and increased shoulder flexion to a greater extent at the end ranges (course 5 in particular).

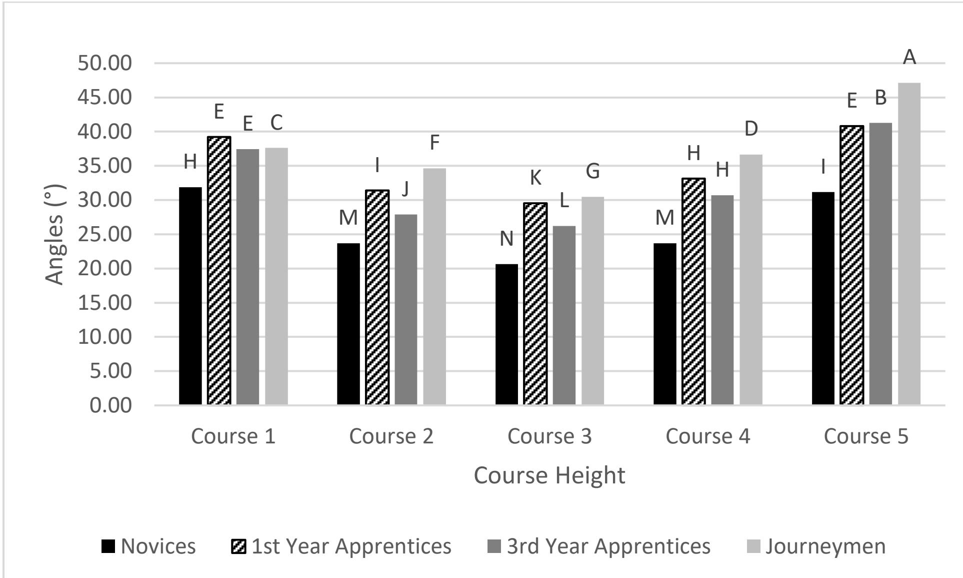


Figure 9: Interaction Effect of Experience Group and Course Height on Mean Right Shoulder Flexion

For novices and 3rd year apprentices, left shoulder abduction increased from course 1-5 (Figure 10). For 1st year apprentices and journeymen, left shoulder abduction increased from courses 2-5. 1st year apprentices had significantly higher left shoulder abduction compared to all other groups at courses 1-3 (lower courses). Journeymen have the highest abduction at course 5 by up to 41.3% (7.0°). Novices had significantly lower abduction compared to all other groups at each course height by 36.0-80.3% (2.2°-11.5°). The largest difference within experience groups occurred for journeymen (17.8°) while the smallest occurred for 1st year apprentices (6.9°). Course height had a larger impact on differences between max and min shoulder flexion compared to experience. 1st year apprentices maintain high levels of left shoulder abduction even at the lower levels and maintain the most similar levels of abduction from courses 1-5. Journeymen, on the other hand, had lower left shoulder abduction at the lower courses but increased it to a greater extent at the highest course height.

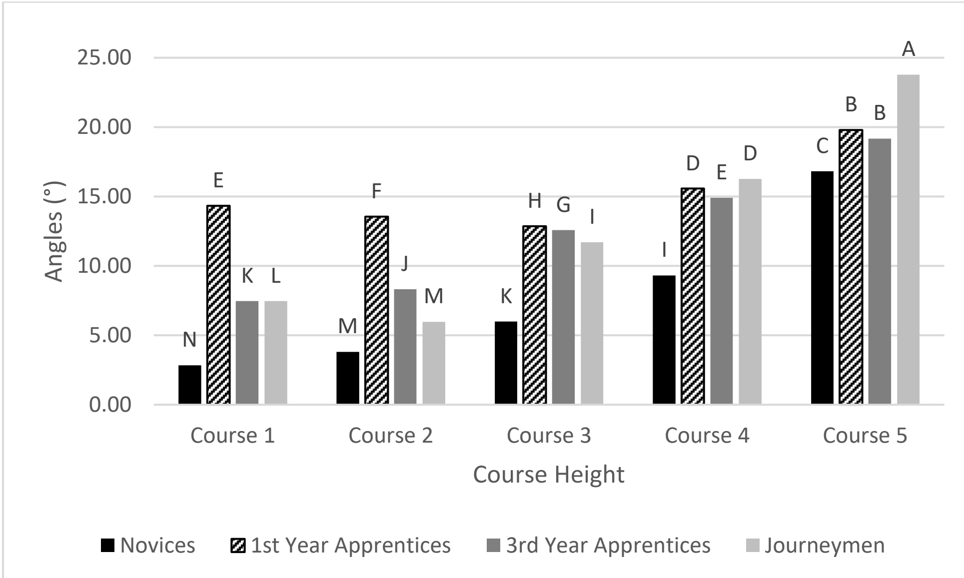


Figure 10: Interaction Effect of Experience Group and Course Height on Mean Left Shoulder Abduction

Novices increased right shoulder abduction from courses 1-5. 3rd year apprentices and journeymen decreased or maintained the same right shoulder abduction from courses 1-2 and then increased abduction from courses 2-5 (Figure 11). At each course height, 3rd year apprentices had the highest right shoulder abduction compared to all other groups by 5.4-59.6% (0.9°-6.6°). Within course height, the difference between the maximum and minimum right shoulder abduction for novices was 12.1°, for 1st year apprentices it was 3.2°, for 3rd year apprentices it was 8.4° and for journeymen the difference was 11.4°. Within experience groups, the lowest difference occurred between the apprentice groups at course 1 (5.8°) whereas the highest difference occurred between the apprentice groups at course 5 (9.5°). For right shoulder flexion, journeymen had lower right shoulder abduction compared to the apprentice groups at courses 1-3 and increased the amount of shoulder abduction at the higher course heights (4 and 5) to a greater extent than the apprentice groups. 1st year apprentices noticeably maintained similar levels of right shoulder abduction from courses 1-3. This is similar to the trend at left shoulder abduction, but rather than maintain high levels of abduction at lower course heights, novices maintained lower levels of abduction at higher course heights.

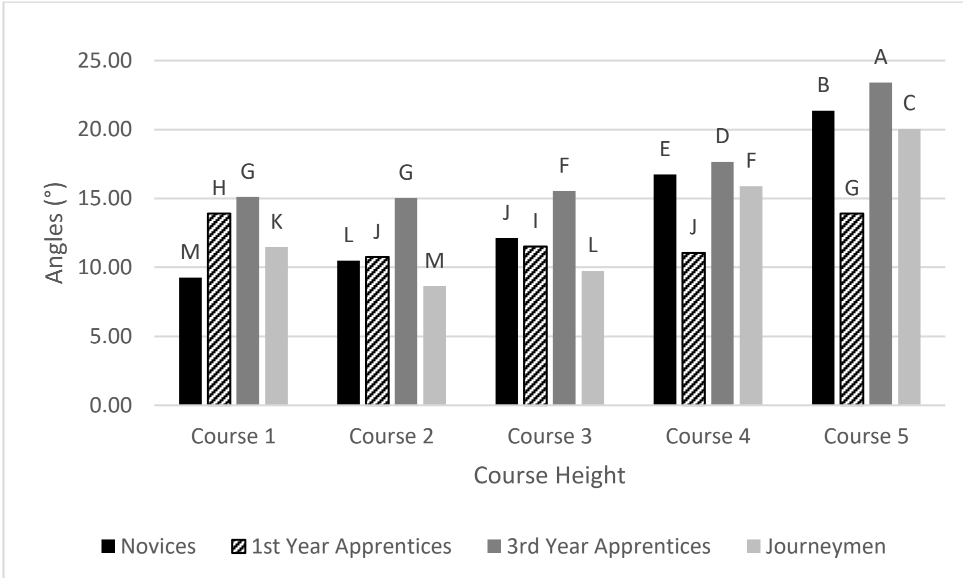


Figure 11: Interaction Effect of Experience Group and Course Height on Mean Right Shoulder Abduction

Torso flexion was highest at course 1, across all courses and experience groups (Figure 12). Within experience group, torso flexion was lowest at courses 3 and 4. Within experience groups, torso flexion decreased from courses 1 to 4, then increased at course 5; however, one explanation may be that because this data encompasses the entire task, at course 5 (highest lay-down) participants have the lowest pick-up height, which results in increased torso flexion. Within each course, 3rd year apprentices had the highest degree of torso flexion and was significantly higher compared to all other groups except in course 3, where torso flexion was not significantly higher than journeymen. The largest differences between experience groups occurred at course 1 (8.8°), while the smallest differences occurred at courses 3 and 4 (2.6°-2.9°). Coincidentally, the largest differences occurred at instances of highest torso flexion and low back compression and the lowest differences occurred at instances of low overall torso flexion (and among the lowest low back compression forces). Course height had a greater impact on overall torso flexion within groups; however, experience group also played a role, especially at course 1. The greatest difference in torso flexion between course heights was in journeymen with a difference of 16.8°. The largest difference caused by experience group was between novices and 3rd year apprentices at course 1 (8.8°).

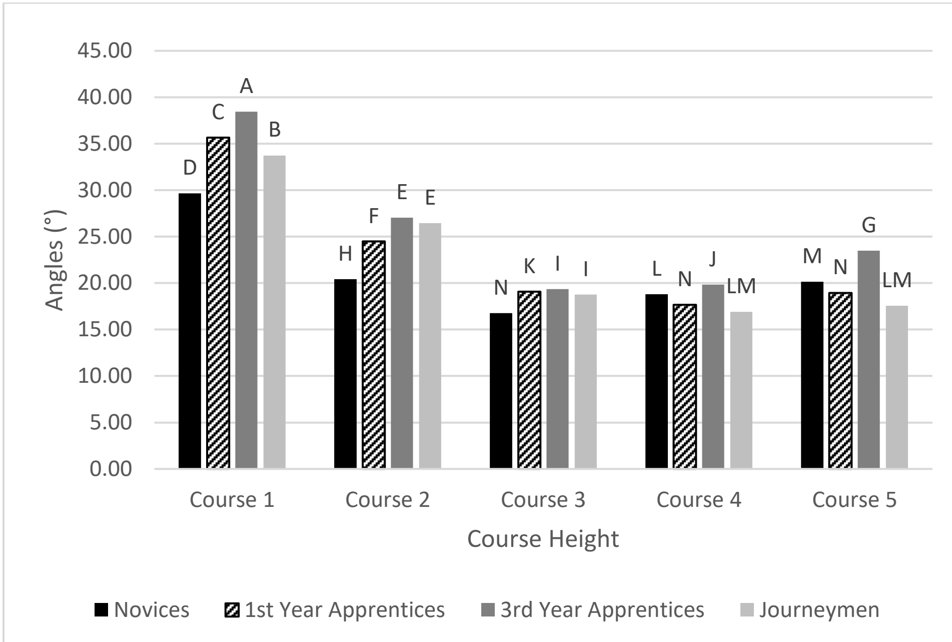


Figure 12: Interaction Effect of Experience Group and Course Height on Mean Torso Flexion

For most course heights, both 1st year apprentices and journeymen favored side bending to the left side, while novices and 3rd year apprentices tended to bend to the right side (Figure 13). Journeymen had a lot of side bending to the left at course 1 but it was significantly lower with each increase in course height. At the 5th course, journeymen only had 0.3° of side bending to the right side. At course 5 journeymen had lower torso bending by 102.1% (14.3°) compared to course 1. For journeymen, side bending is a strategy used at lower courses, but used less so at higher courses. Between the maximum and minimum levels of side bending for 1st year apprentices there is only a difference of 4.6°, compared to 5.5° for novices, 6.2° for 3rd year apprentices and 14.3° for journeymen. This demonstrates that 1st year apprentices are at highest risk due of MSDs due to consistent side bending at each course height.

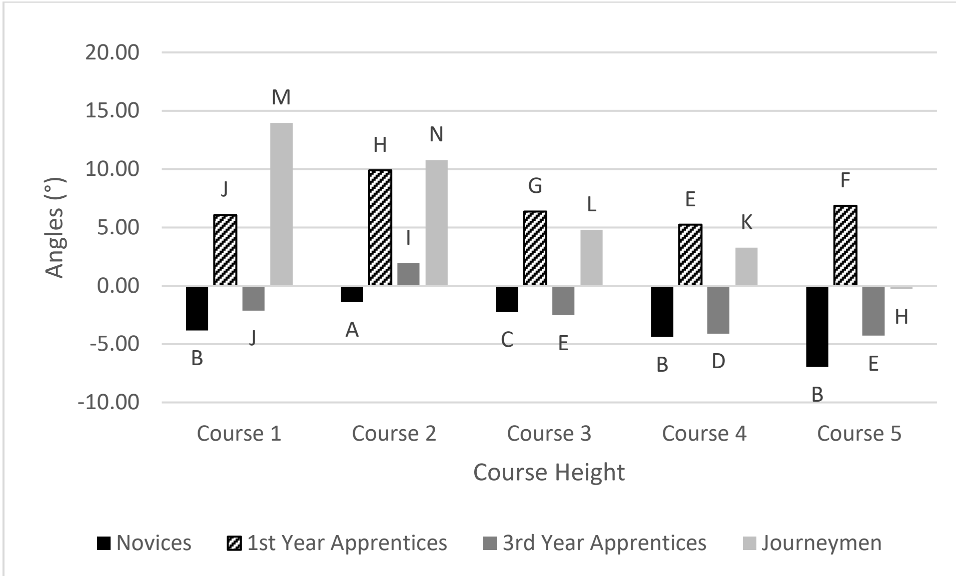


Figure 13: Interaction Effect of Experience Group and Course Height on Mean Torso Side Bending

At each course height, 1st year apprentices had either the highest or second highest amount of side bending compared to all other groups (in both mean values and absolute mean values; Figure 14). With regards to the absolute values of mean torso side bending, journeymen and novices had the highest amount of side bending at courses 1-3. Overall, 3rd year apprentices and novices had the least amount of torso side bending; however, both groups had the least side bending at the lower courses (1-3) and higher side bending at the higher courses (4 and 5). At courses 4 and 5, both groups had higher absolute values of side bending compared to journeymen. This trend of increased absolute torso side bending at higher courses follows an opposite pattern to journeymen who have decreased absolute side bending at higher courses.

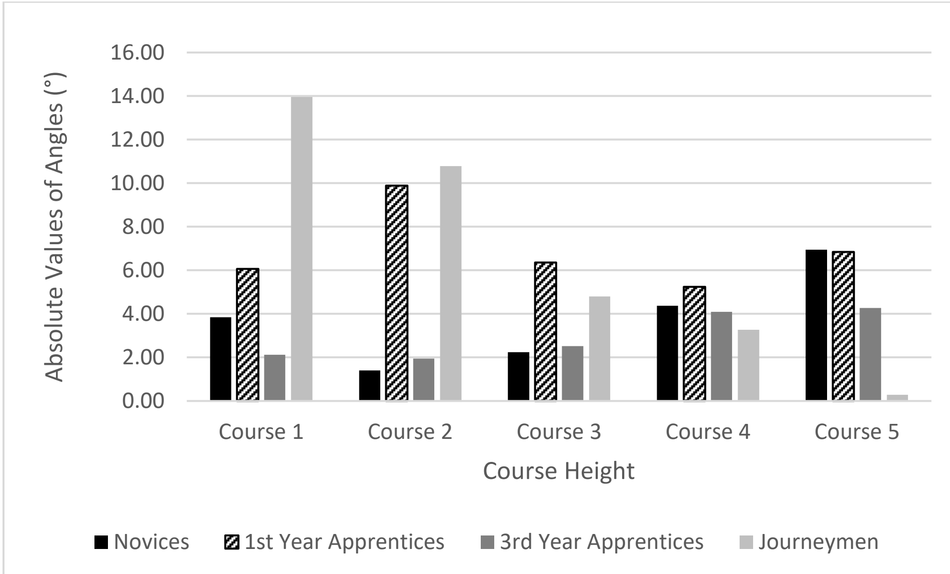


Figure 14: Absolute Values of Mean Torso Side Bending Distance by Experience Group and Course Height

Journeymen and 1st year apprentices tended to twist to the left, with the exception of course 4 where journeymen favored the left side (Figure 15). For courses 1 to 4, 3rd year apprentices tended to twist to the left as well, but novices tend to twist to the right.

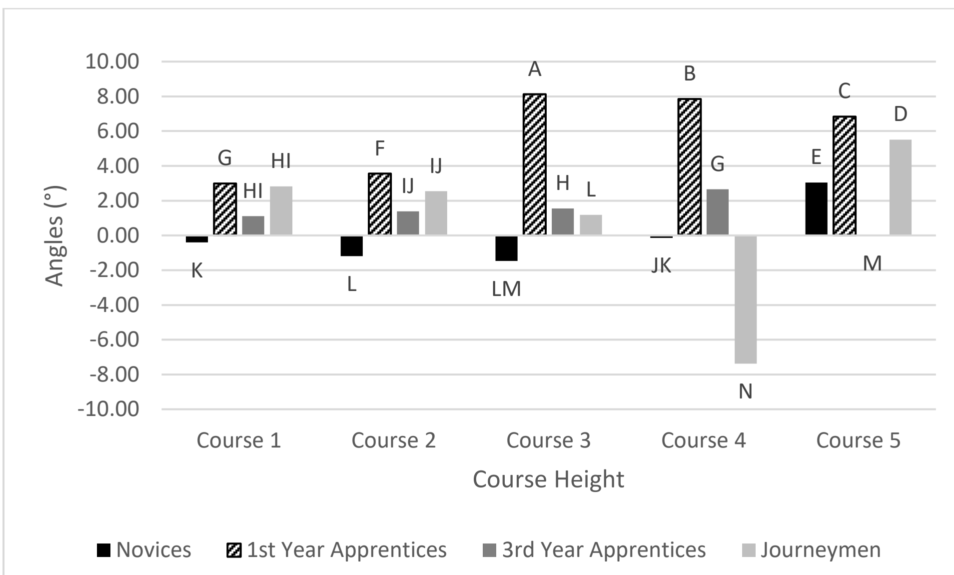


Figure 15: Interaction Effect of Experience Group and Course Height on Mean L5/S1 Axial Twist

At each course novices and 3rd year apprentices had the most neutral torso posture (least absolute value for axial twist; Figure 16). For 1st year apprentices, the highest magnitude of twisting occurred at courses 3 to 5. For journeymen, the highest magnitude of twisting (absolute value) occurred at courses 4 and 5. Similarly, the highest magnitude of twisting for novices occurred at course 5, and the highest magnitude for 3rd year apprentices occurs at course 4. Higher magnitudes of twisting occurred at the higher course levels at which participants have a more upright posture. For courses 1-3, journeymen had significantly lower axial twist compared to 1st year apprentices by up to 85.3% (6.9°). Journeymen had similar levels of twisting as 3rd year apprentices at courses 1 and 2. When comparing the values and the absolute values of axial twist, course height had the greatest impact on joint angles for journeymen (a difference of 12.9° and 6.2°, respectively) followed by 1st year apprentices (5.1° for both values and absolute values). Experience had the largest impact at course 4: between 1st year apprentices and journeymen with a difference of 15.2° in absolute values; between 1st year apprentices and novices for absolute values with a difference of 7.7°. One of the main differences was that journeymen had minimal L5/S1 axial twist at course 3 while novices had a significantly higher axial twist compared to all other groups. Journeymen only increased the amount of twisting at the higher courses (4 and 5). At these courses, they can adopt more upright postures with less back flexion (as demonstrated in k-means cluster analysis). At higher courses journeymen may use higher torso twisting as a strategy to increase productivity.

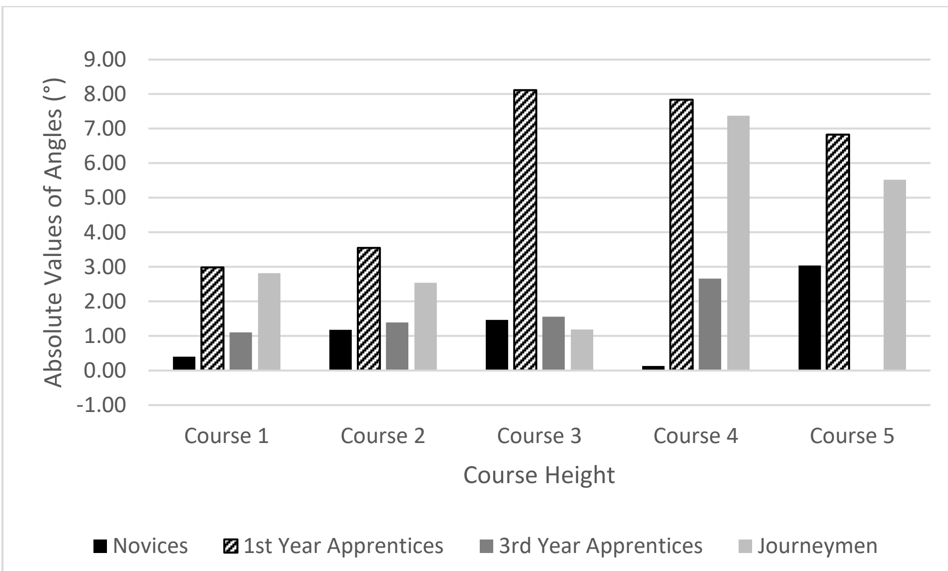


Figure 16: Absolute Values of Mean L5/S1 Axial Twist Distance by Experience Group and Course Height

For novices, 3rd year apprentices and journeymen, there was a significant decrease of mean left hip flexion within the experience group from courses 1 to 5 (Figure 17). For 1st year apprentices there was a significant decrease from courses 1 to 4, between courses 4 and 5 there is no significant change in left hip flexion. At each course height, journeymen had significantly higher left hip flexion compared to both apprentice groups. For courses 2-5 novices had significantly higher left hip flexion compared to both apprentice groups. There were larger differences in mean left hip flexion across course heights compared to experience groups. The largest difference in left hip flexion due to course height was in journeymen from course 1 to 5 (26.7°). The smallest difference in left hip flexion due to course height was in novices (16.6°). Conversely, the largest difference in left hip flexion due to experience group was at course 2 between 3rd year apprentices and journeymen (15.0°). For courses 1 to 3, journeymen had significantly higher left hip flexion compared to novices by up to 20.1% (8.8°), but slightly lower flexion at courses 4 and 5. Journeymen had significantly higher overall hip flexion compared to apprentice groups at each course height and higher overall hip flexion compared to novices at the lower course heights (1-3). Journeymen also had the largest difference in left hip flexion from courses 1 to 5 whereas, novices had the least difference.

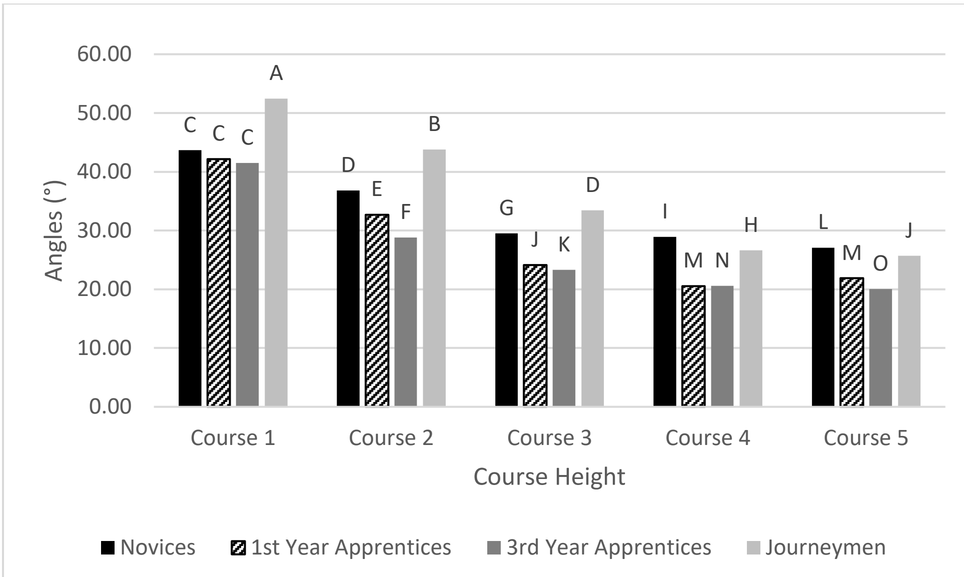


Figure 17: Interaction Effect of Experience Group and Course Height on Mean Left Hip Flexion

For both novices and journeymen, there was a decrease within the experience group from courses 1 to 5 for mean right hip flexion (Figure 18). For both apprentice groups there was a decrease of right hip flexion from courses 1 to 4, but the same or an increase in right hip flexion at course 5. At each course height, journeymen and novices had significantly higher right hip flexion compared to both apprentice groups. There were larger differences in mean right hip flexion across course heights compared to experience groups. The largest difference in right hip flexion due to course height was in journeymen from course 1 to 5 (29.7°). The smallest difference in right hip flexion due to course height was in novices (14.5°). Conversely, the largest difference in right hip flexion due to experience group was at course 2 between 3rd year apprentices and journeymen (16.3°). For courses 1 to 3, journeymen had significantly higher left hip flexion compared to novices by up to 26.7% (11.5°), but lower flexion at courses 4 and 5.

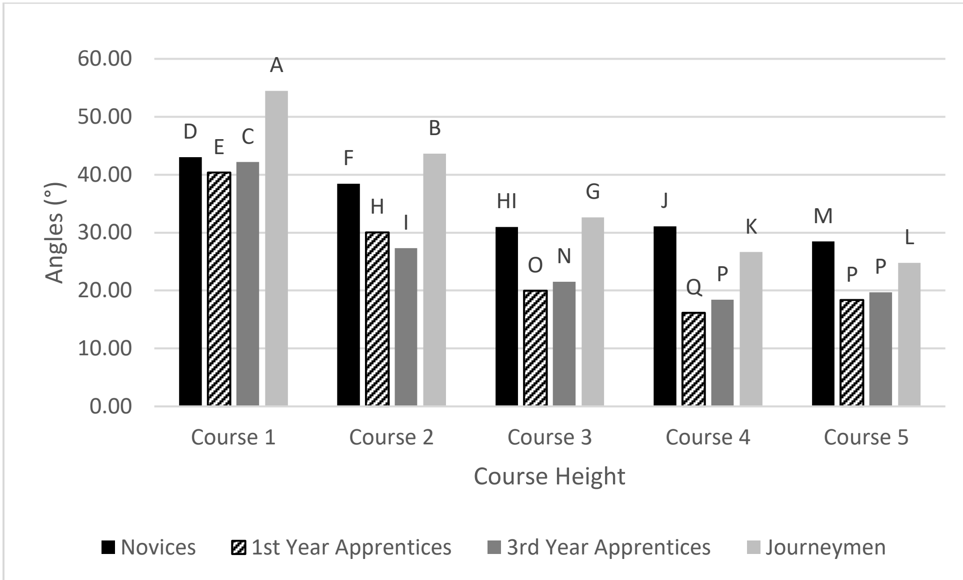


Figure 18: Interaction Effect of Experience Group and Course Height on Mean Right Hip Flexion

At both the left and right hip, although both journeymen and novices typically had significantly higher hip flexion than both apprentice groups, novices maintained a more similar level of left hip flexion across each course height whereas journeymen increased the amount of hip flexion to a greater extent at the lower courses. Apprentice groups increased hip flexion to a greater extent from the higher courses relative to the lower courses but did not have a large enough magnitude of hip flexion overall.

At courses 4 and 5 most experience groups carried the CMU above the hips, whereas for the lower courses (1-3) all experience groups carried the CMU below hip height (Figure 19). Within each experience group, participants carried the CMU at progressively higher heights with respect to the ground, with each increase in course height. At the lower courses (1-3), journeymen carried the CMU significantly lower (closest to the ground) compared to all other groups and 1st year apprentices carried the CMU significantly higher (away from the ground) compared to the other groups. 3rd year apprentices carried the CMU second lowest after journeymen, which may be a strategy to increase productivity. However, at the higher courses (4 and 5), both 1st year apprentices and journeymen carried the CMU significantly higher than the other groups (farther above the hips).

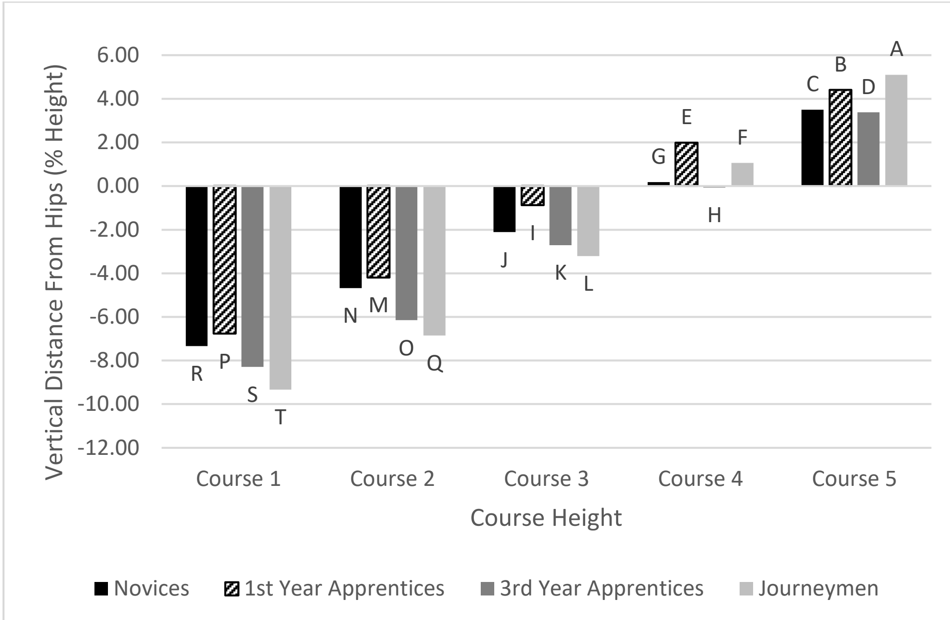


Figure 19: Interaction Effect of Experience Group and Course Height on Mean Vertical Carrying Distance

Within experience groups, participants carried the CMU closer to their body from courses 1 to 3 (Figure 20). Journeymen carried the CMU significantly closer to their bodies as course height increased. For all other groups, there was not strictly a decrease; there was a significant increase in anterior carrying distance at either course 4 or 5. For courses 1 to 4, at each course height journeymen had significantly higher anterior carrying distance compared to all other groups. At the higher courses (4 and 5) there was the least difference between experience groups for anterior carrying distance, and the largest difference at course 2. Within experience groups, journeymen had the largest range of anterior carrying distance from course 1 to course 5 (difference of 6.4% height) whereas 3rd year apprentices had the smallest range (difference of 3.5% height). Perhaps at lower courses, when bending at hips and pushing hips back, carrying the CMU farther away from the body can act as a counterbalance.

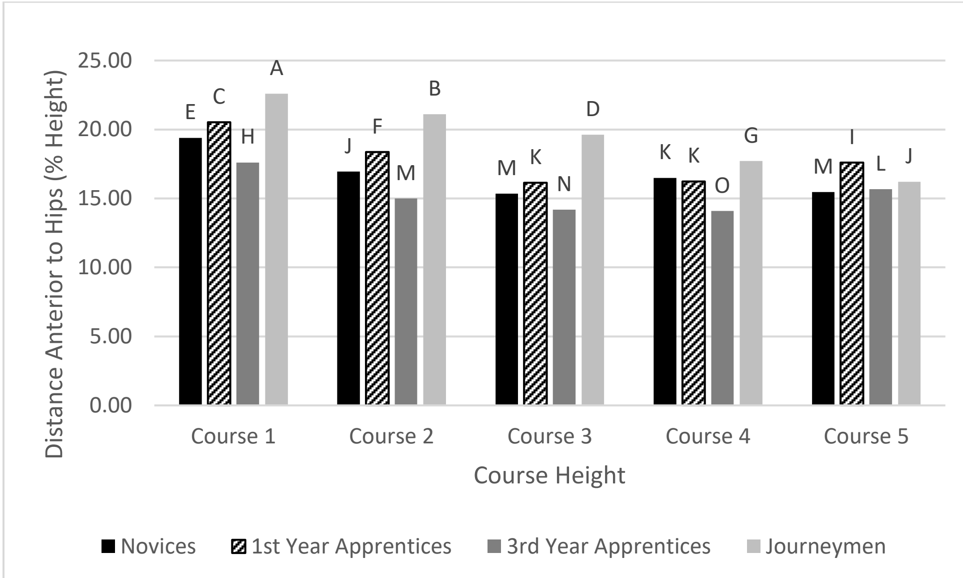


Figure 20: Interaction Effect of Experience Group and Course Height on Mean Anterior Carrying Distance

Interestingly, both 3rd year apprentices and journeymen favored staggering their stances with their left foot forward while novices and 1st year apprentices more often staggered their stances with their right foot forward (Figure 21). Journeymen had the lowest values of A/P stance distance (left foot anterior) compared to all other groups by up to 277.2% (9.6% of height). Among experience groups, novices had the highest range between course levels (4.9% height), likely because which foot was forward changed from course 1 to the rest of the courses.

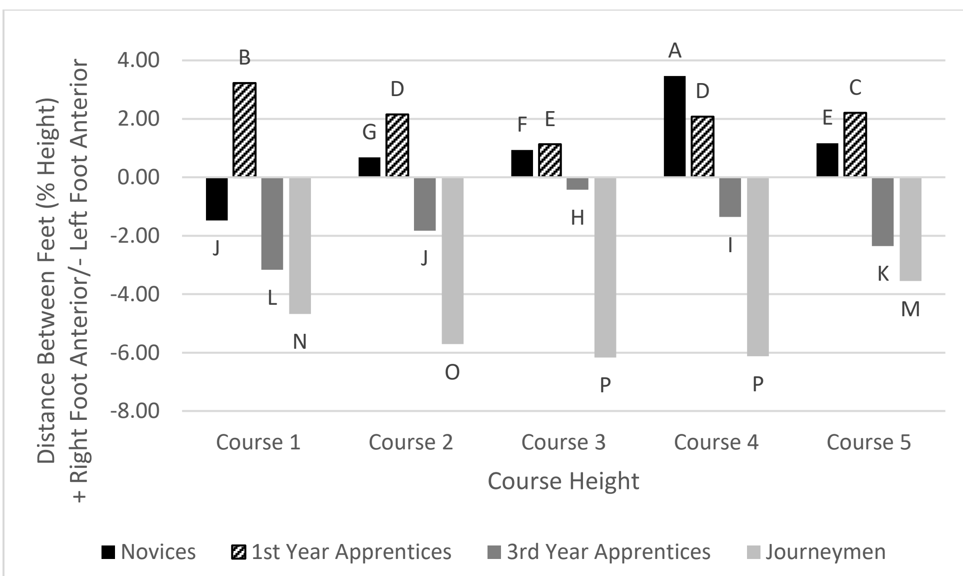


Figure 21: Interaction Effect of Experience Group and Course Height on Mean Anterior/Posterior Stance Distance

Across all course heights, journeymen had the highest absolute values of A/P stance distances by up to 1334.9% (5.7% of height; Figure 22). Novices had the highest A/P stance distance at course 4, followed by courses 1 and 5, and the lowest at courses 2 and 3. Journeymen had the highest A/P stance distance at courses 3 and 4, and lowest at courses 1 and 5. However, both apprentice groups had the highest A/P stance distance at course 1 followed by course 5, and lowest A/P stance distance at course 3, which is the opposite trend from journeymen. For both the mean A/P stance distances and the absolute values of mean A/P stance distances, the effect of experience created greater differences in A/P stance distance compared to the effect of course height.

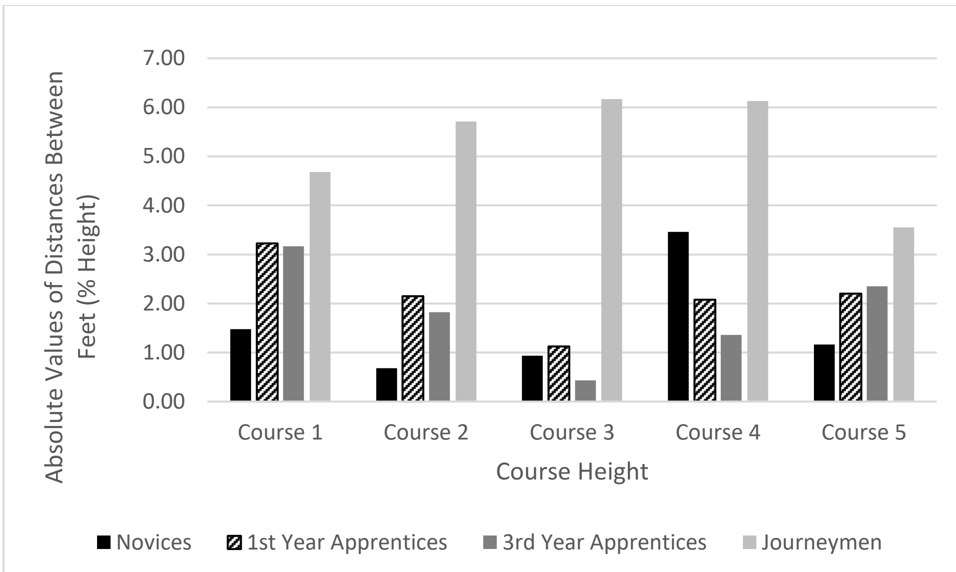


Figure 22: Absolute Values of Mean Anterior/Posterior Stance Distance by Experience Group and Course Height

3.4.2 Effect of Experience on Kinematics

Neck flexion was significantly higher in the 3rd year apprentice groups compared to the other groups by 67.6-372.0% (5.4°-10.5°). Journeymen had the lowest average neck flexion (2.8°) followed by novices (5.5°). Higher neck flexion contributed to higher low back compression forces due to the increased moment arm of the center of mass of the head. Both right and left shoulder flexion followed the same trends. Journeymen followed by 1st year apprentices had the highest shoulder flexion (36.0°-37.9° and 34.7°-34.9°, respectively) while novices had the least (26.2°-27.9°). For left shoulder flexion, journeymen had higher flexion by 3.9-29.0% (1.34°-8.1°) compared to all other groups and for right shoulder flexion, they had higher flexion by 8.6-44.4% (3.0°-11.6°). Left and right shoulder abduction followed different patterns. The two groups with the highest shoulder abduction for the left shoulder, 1st year apprentices and journeymen, had the least amount of should abduction for the right shoulder, and vice versa. This may signify that the amount of overall average shoulder abduction is asymmetric, and one shoulder will abduct more while the other will abduct less. For left shoulder abduction 1st year apprentices had the highest amount of abduction (15.4°) by 9.5-78.5% (1.3°-6.8°) compared to the other groups and for right shoulder abduction, 3rd year apprentices had the highest abduction (17.8°) by 20.3-45.6% (3.0°-5.6°) compared to other groups.

For torso flexion, the 3rd year apprentices had the highest amount of flexion (24.7°) compared to the other groups by 9.2-19.5% (2.1°-4.0°). Novices had the least amount of torso flexion (20.7°) followed by journeymen (21.8°). This is a similar pattern to neck flexion and is unsurprising given that it follows the trend for average low back compression forces. As torso flexion increases, the magnitude of low back compression forces increases as well. For other angles at the low back, 1st year apprentices had the highest average torso side bending (6.9°) followed by journeymen (5.7°), both to the left side. Conversely, novices and 3rd year apprentices had torso bending to the right side. Overall, the amount of torso bending was relatively small because it was averaged over the entire task. Similarly, levels of average axial twist at the L5/S1 joint were minimal for all groups (< ~1.3°) except for 1st year apprentices with an average of 6° of L5/S1 axial twist to the left. Left and right hip flexion both had similar trends with journeymen having the highest amount of hip flexion (34.7°-34.8°) followed by novices (32.2°-33.5°). Both apprentice groups had the lowest amount of left and right hip flexion (24.2°-27.6°). Journeymen had significantly higher left and right hip flexion by 8.2% (2.6°) and 3.7% (1.2°) compared to novices, by 26.3% (7.3°) and 43.6% (10.5°) compared to 1st year apprentices and by 36.0% (9.2°) and 41.6% (10.2°) compared to 3rd year apprentices. The apprentice groups demonstrated similar patterns of lower hip flexion, while the novice and journeyman groups demonstrated similar patterns of high hip flexion. Both groups with higher hip flexion also had lower low back compression and shear forces. These groups offload the back and use hip flexion to get closer to the ground at low working heights.

When averaged across the entire task, journeymen had the highest anterior carrying distance by 8.0-25.6% compared to all other groups. Conversely 3rd year apprentices had the lowest anterior carrying distance, followed by novices. This was unexpected since larger anterior carrying distances of the CMU would contribute to higher loads on the low back. However, 3rd year apprentices had the highest average L4/L5 compression force and journeymen had the 2nd lowest. Journeymen have been shown to be the most productive group; therefore, journeymen may carry the CMU a bit further from the body as a part of an overall strategy for faster task completion times while using other strategies to minimize low back compression forces (e.g., higher hip flexion and lower neck flexion etc.).

Overall averaged vertical carrying distance had a small range between groups (between 0.7-2.1% height below hips) and all groups all carried the CMU below hip height. However, 3rd year apprentices carried the CMU closest to the ground compared to all other groups. Lastly, for A/P stance distance, both novices and 1st year apprentices stood with their right foot forward while 3rd year apprentices and journeymen stood with the left foot forward when averaged across the entire task. Journeymen had the largest absolute A/P stance distance (5.2% height) compared to all other groups by 143.7-351.3% (difference of approx. 3.1-4% height). The full results including figures and the values and significance levels of the main effect of experience are presented in Appendix E.

3.4.2.1 Peak Frame Analysis of L4/L5 Compression Force

At peak L4/L5 compression, both apprentice groups were above the established threshold denoting MSD risk for the low back, with the 3rd year apprentices experiencing the highest loads, followed by the 1st year apprentices. Both novices and journeymen had the lowest compression forces compared to the other groups. This is a trend in compression forces across the entire task, and is reflected again at postures of peak compression, but with much higher average compression forces that exceeded thresholds. The differences between experience groups were exacerbated at instances of increased risk, e.g., lower courses. For this reason, the differences across experience groups at peak forces were analyzed. At peak compression, novices and journeymen were exposed to lower joint loads due to their strategies of minimizing neck flexion, torso asymmetry, as well as increasing left and right hip flexion.

Compared to average joint angles across the entire task, at peak L4/L5 compression force, shoulder flexion, torso flexion, hip flexion, and anterior carrying distance were higher, while vertical carrying distances were lower. Torso side bending and axial twist for the 1st year apprentice group was higher as well. Left and right shoulder flexion ranged from 40.3°-50.3° at peak L4/L5 compression compared to 26.2°-37.9 across the entire task. Torso flexion ranged between 41.8°-49.0° at peak L4/L5 compression compared to 20.7°-24.7° across the entire task. Similarly, hip flexion ranged between 44.8°-59.5° at peak L4/L5 compression compared to 24.2°-34.8° across the entire task; anterior carrying distance ranged between 19.9-23.0% height at peak L4/L5 compression compared to 15.2-19.1% height across the entire task; and vertical carrying distance ranged between 11.5-12.4% height below hips at peak L4/L5 compression compared to 0.7-2.1% height below hips across the entire task. Lastly, the 1st year apprentice group had higher torso side bending to the left by 108.6% (7.4°) and slightly higher L5/S1 axial twist by 5.2% (0.3°) at peak L4/L5 compression compared to the entire task. The increase in certain joint angles that are seen in peak compression postures compared to the entire task are unsurprisingly, those in the sagittal plane, that increase the moment arm at the low back.

Across the entire task, experts typically had higher anterior carrying distances than the other groups, but at peak L4/L5 compression, there were large increases in anterior carrying distances for apprentice groups while there were only small increases in distance for experts. This may signify that increases in carrying distances by apprentices are accompanied by an increase in compression whereas, experts are able to maintain a larger carrying distance while minimizing overall low back compression through other factors such as lifting technique, strength, or expertise. To further probe this relationship, the anterior carrying distance at peak compression per participant was compared post-hoc, which revealed that novices had the highest anterior carrying distance (28.1% height), followed by 1st year apprentices (26.4% height), 3rd year apprentices (25.3% height) and lastly, experts (21.6% height). However, the differences between experience groups were insignificant, due to lack of statistical power from the reduced sample size. Nevertheless, this may be indicative that there is an optimal range for carrying distance. While experts typically carry the CMU further anteriorly, there is a point at which high anterior carrying distances can be detrimental, and conducive to high L4/L5 compression forces. Larger anterior carrying distances contributing to higher compression forces at the low back aligns with biomechanical principles due to the increased moment arm. However, before this threshold, experts may benefit from slightly higher anterior carrying distances, perhaps in productivity, better line of sight, or reductions in bending at the neck, trunk, or hips.

Both torso flexion and vertical carrying distance were the top two contributors to L4/L5 compression for all groups, but there were no significant differences between experience groups. Neck flexion was the third contributor for 3rd year apprentices, as the only group with neck flexion >0.7°. Anterior carrying distance was a higher-ranking contributor for both 1st year apprentices and journeymen because these groups had significantly higher anterior carrying distances compared to the other groups.

3.4.2.2 Peak Frame Analysis of L4/L5 Anterior/Posterior Shear

The analysis at peak anterior posterior shear supported findings found in the full task analysis and the peak frame analysis of L4/L5 compression force. Torso flexion, vertical carrying distance and hip flexion were all among the top contributors to peak A/P shear forces across groups. These factors all play a major role in contributing to joint loads at the lower back. Furthermore, torso and hip flexion increased at peak A/P shear compared to the entire task, and vertical carrying distances decreased compared to the entire task. Additionally, anterior/posterior stance distance was the second ranked contributor to peak A/P shear force in journeymen, who coincidentally also had the largest magnitude of A/P stance distance. A/P stance distance in journeymen also increased from the entire task to peak A/P shear force by 24.3% (1.3°). Neck flexion is the 4th ranked contributor in 3rd year apprentices and the highest flexion angle for 3rd year apprentices compared to other groups.

3.4.2.3 Peak Frame Analysis of L4/L5 Lateral Shear

At peak L4/L5 lateral shear, there were some similar trends to peak L4/L5 A/P shear and compression forces. For example, trends for neck flexion were the same, as well as trends for torso side bending, and L5/S1 axial twist, and left and right hip flexion. While the trends for shoulder flexion and abduction differed, they were not notable in contribution to L4/L5 lateral shear force based on the predictor analysis.

At both peak L4/L5 A/P shear and lateral shear forces, the overall average torso flexion, and hip flexion across groups increased while vertical carrying distance decreased compared to the entire task. Average shoulder flexion across groups was also higher compared to the entire task. For 1st year apprentices, torso side bending and L5/S1 axial twist wes higher at peak L4/L5 A/P and lateral shear compared to the entire task. Furthermore, at peak L4/L5 lateral shear force, the average anterior carrying distance across groups wes higher compared to the entire task.

In the predictor screening, there was little variation in the top ranked contributors across experience groups. The top contributors were the main kinematic variables that would be expected to contribute to high L4/L5 lateral shear forces, as well as the kinematic variables that increased/decreased in overall averages from the entire task such as torso flexion, hip flexion, neck flexion and anterior and vertical carrying distance. The predicted contribution of left wrist deviation, especially for journeymen, but 3rd year apprentices as well was an interesting result. Compared to the entire task, left wrist deviation increased for all experience groups. For journeymen, left wrist ulnar deviation increased by 72.4% (4.5°) but for journeymen it only increased by 2.3% (0.3°) compared to the entire task. Nevertheless, at peak L4/L5 lateral shear force, left wrist deviation angles ranged from 10.7° to 17.6° across all groups, compared to 6.2°-13.0° for the entire task.

3.4.2.4 Peak Frame Analysis of Left and Right Shoulder Moments

The peak frame analysis at peak left and right shoulder moments supported earlier findings from the full lift analysis regarding the effect of experience group on kinematic variables. Similar findings to the full lift analysis for the different instances of peak loads at both the low back and shoulder reveal that the full lift analysis had enough discriminatory power to draw conclusions about the effect of experience on aspects of lifting technique.

Compared to the average left and right shoulder flexion across the entire task (26.2°-37.9°), the average shoulder flexion at peak left shoulder moment (35.1°-49.6°) and at peak right shoulder moment (37.1°-46.7°) was higher for each group. This is expected since higher shoulder flexion would contribute to a higher shoulder moment. Interestingly, the level of abduction at peak left and right shoulder moment did not follow the same trend. In fact, for all but one case, left and right shoulder abduction was lower at peak left and right shoulder moment compared to the averages across the entire task.

Compared to the average torso flexion (20.7°-24.7°) across the entire task, torso flexion at peak left shoulder moment (34.2°-44.6°) and peak right shoulder moment (36.4°-41.4°) was much higher. Additionally, side bending to the left of the 1st year apprentice and journeymen groups (14.3°-16.9°) was higher at peak left shoulder moment compared to the entire task (5.7°-6.9°). Whereas, at peak right shoulder moment, novice and 3rd year apprentice groups had higher torso side bending to the right (11.3°-11.4°) compared to the entire task (2.5°-4.0°). For the entire task, torso side bending of novices and 3rd year apprentices favored the right side while 1st year apprentices and journeymen favored the left side. At peak shoulder moment, all groups had higher side bending towards the side of the respective shoulder. This was most apparent in the experience groups that favored torso side bending to the ipsilateral side. These groups had an increase in magnitude of torso side bending in comparison to the other groups, which had a decrease in bending to the opposite direction. This asymmetrical posture at the trunk is likely reflective of an asymmetrical load at the shoulder leading to peak moments on the affected side.

Overall hip flexion was higher at postures of peak left shoulder moment (40.0°-50.1°) and peak right shoulder moment (35.0°-52.2°) compared to the entire task (24.2°-34.8°). Participants at peak left and right shoulder moment carried the CMU farther from the body on average (19.6% and 18.4% respectively), compared to the entire task averages (~17.1%). Furthermore, participants held the CMU much lower to the ground at peak left shoulder moment (8.6-10.6% height below hips) and peak right shoulder moment (7.5-10.4% height below hips) compared to the entire task (0.7- 2.1% height below hips). Holding the CMU farther from the body results in higher moment arms for the back and shoulder and carrying the CMU closer to the ground can also result in awkward postures or reaching at the shoulder.

The top predicted contributors to peak left shoulder moment were angles at the hips, torso, neck and left shoulder, as well as vertical and anterior carrying distance. The top predictor contributors to peak right shoulder moment were similar except had right shoulder angles rather than left shoulder. Compared to the entire task, vertical carrying distance decreased, and average anterior carrying distance across groups increased. Overall magnitudes of torso flexion, hip flexion and shoulder flexion increased as well at peak shoulder moment. This is demonstrative that angles at the torso and anterior and vertical carrying distances are also important postural factors leading to peak moments at the shoulder in addition to shoulder flexion and abduction.

3.4.3 Forces and Moments

Sections 3.4.1 and 3.4.2 outline significant effects of experience level on kinematic variables, demonstrating that experts, apprentices, and novices use distinct strategies while laying CMUs for a standard wall. This section provides supplementary data on the kinetics measured during a standard wall build and highlights the outcome of the kinematic differences on joint forces and moments at the low back and shoulder.

There was a significant main effect of experience group on mean L4/L5 compression and mean left shoulder moment, as well as a significant interaction effect of experience group and course height on mean L4/L5 compression forces (Table 7). The same dataset was used for the force calculations of the mean L4/L5 compression forces and mean right and left shoulder moment as the data reported in Ryu et al. (2020a). However, this thesis treated the data differently, used a different analysis method and reports not only the main effect of experience but the interaction effect of experience group and course height. The mean L4/L5 compression forces and right and left shoulder moments were critical to provide additional context to this thesis and is directly related to the analysis of postural variables. Further analysis of the body loads of masons by experience group is reported by Ryu et al. (2020a).

Table 7: Main and Interaction Effects of Experience Group and Course on Joint Loads

Variable	Experience Group **Prob > F**	Experience Group* Course **Prob > F**
Mean L4/L5 Compression Forces	**<.0001***	**<.0001***
Mean L4/L5 A/P Shear Forces	.	.
Mean L4/L5 Lateral Shear Forces	.	.
Mean Left Shoulder Moment	**0.0423***	0.9985
Mean Right Shoulder Moment	0.2550	0.9635

*Significant effects denoted in bold ($p<0.05$)

When comparing the mean forces and moments at the lower back and shoulder by experience group, the 3rd year apprentices had the highest forces for L4/L5 compression, anterior/posterior shear, lateral shear, and both left and right shoulder moments (Table 8 and Figure 23). The 1st year apprentices also had the second highest loads for all mean forces and moments. The lowest and second lowest loads switched between the novice group and the journeymen, depending on the measurement. Novices had the lowest mean L4/L5 compression forces and mean left shoulder moment, while journeymen had the lowest mean L4/L5 anterior/posterior and L4/L5 lateral shear forces as well as mean right shoulder moment.

The mixed effect model indicated a significant main effect of experience group for the mean L4/L5 compression forces and the mean left shoulder moments (Table 8 and Figure 23). For the mean L4/L5 compression forces, all the experience groups had significantly difference compression forces. The 3rd year apprentice group had mean L4/L5 compression forces that were 18.5% (361.1 N), 6.2% (135.7 N) and 13.7% (279.1 N) higher than the novices, 1st year apprentices, and journeymen, respectively. Novices, with the lowest compression forces, were only 4% (82.0 N) lower than the journeyman group. However, the mean (1951-2312 N) and median (1838-2147 N) values for all experience groups were well below the NIOSH compression force action limit of 3433 N (NIOSH, 1981; Waters et al., 1993). Similarly, all mean (72-244 N), and median (37-189 N) anterior/posterior and lateral shear forces were below the suggested 700 N action limit for >100 lifts/day and < 1000 lifts/day (Gallagher and Marras, 2012). For the mean left shoulder moment, only the novice group was significantly lower (28%) than the 3rd year apprentice group. Conversely, the 1st year apprentice and journeyman groups were not significantly different from any of the other groups. The novices were exposed to lower forces compared to the journeymen; however, they were also working at a slower speed compared to the other groups and journeymen. Rather than working at a set rate, the masons worked at their usual speed to complete the experimental task. As noted previously, journeymen are the most productive of all groups, and have lower forces compared to both apprentice groups. While novices are safe, they are also the least productive group.

Table 8: Effect of Experience Group on Mean Joint Loads

	Novices	**1st Year Apprentices**	**3rd Year Apprentices**	**Journeymen**
Mean L4/L5 Compression Forces (N)	1950.82 (806.88)	2176.25 (810.05)	2311.90 (1046.63)	2032.83 (773.18)
	A	B	C	D
Mean L4/L5 A/P Shear Forces (N)	188.38 (166.38)	210.25 (194.30)	243.54 (212.33)	154.75 (142.52)
	.	.	.	.
Mean L4/L5 Lateral Shear Forces (N)	77.52 (92.38)	82.15 (97.17)	91.70 (118.40)	72.45 (92.50)
	.	.	.	.
Mean Left Shoulder Moment (Nm)	14.17 (11.92)	17.38 (14.15)	19.68 (15.65)	16.76 (12.90)
	B	AB	A	AB
Mean Right Shoulder Moment (Nm)	15.18 (11.97)	15.43 (12.95)	17.86 (15.88)	15.02 (12.56)
	A	A	A	A

***Significantly different columns indicated by different letters. Columns that share the same level are not significantly different from one another.*

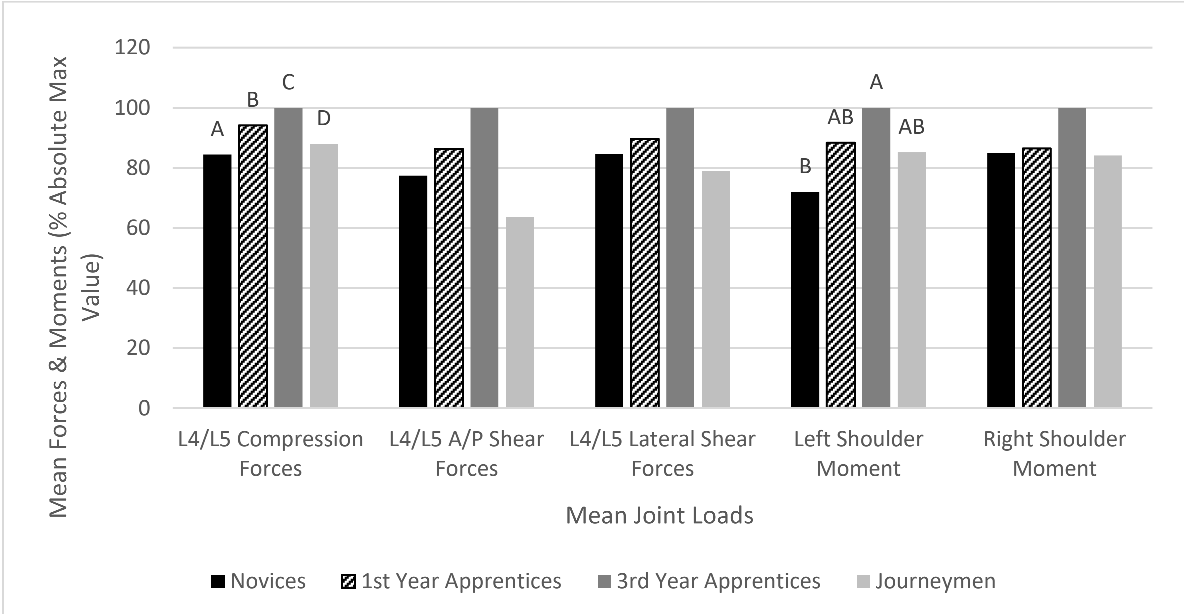


Figure 23: Effect of Experience Group on Mean Joint Loads

**Significantly different columns indicated by different letters. Columns that share the same letter are not significantly different from one another.*

Similar trends across load variables appeared when comparing the median forces and moments at the low back and shoulder (Table 9 and Figure 24). The median values may be more representative due to the long tails in the data; however, the similar trends supported the conclusions made from the mean values. The journeymen had the lowest loads for the median L4/L5 anterior/posterior and L4/L5 lateral shear forces as well as the median right shoulder moment, while novices had the lowest values for the median L4/L5 compression force and median left shoulder moment. One of the differences between the results of the mean loads and the median loads were that instead of the 3rd year apprentices consistently having the highest loads followed by the 1st year apprentices, the highest and second highest loads switched between both apprentice groups. Lastly, another difference is that in the case of the median right should moment, the novices had the highest median load followed by the 3rd year apprentices, then the 1st year apprentices and lastly, the journeymen. The 3rd year apprentices still had the highest median L4/L5 compression forces, median L4/L5 anterior/posterior shear forces and median left shoulder moment.

Table 9: Median Joint Loads by Experience Group

	Novices	1st Year Apprentices	3rd Year Apprentices	Journeymen
Median L4/L5 Compression Forces (N)	1837.79	2045.35	2146.76	1924.91
Median L4/L5 A/P Shear Forces (N)	140.75	152.46	188.57	114.79
Median L4/L5 Lateral Shear Forces (N)	42.04	44.49	42.64	37.02
Median Left Shoulder Moment (Nm)	10.97	14.03	15.54	13.96
Median Right Shoulder Moment (Nm)	12.50	10.91	12.21	10.38

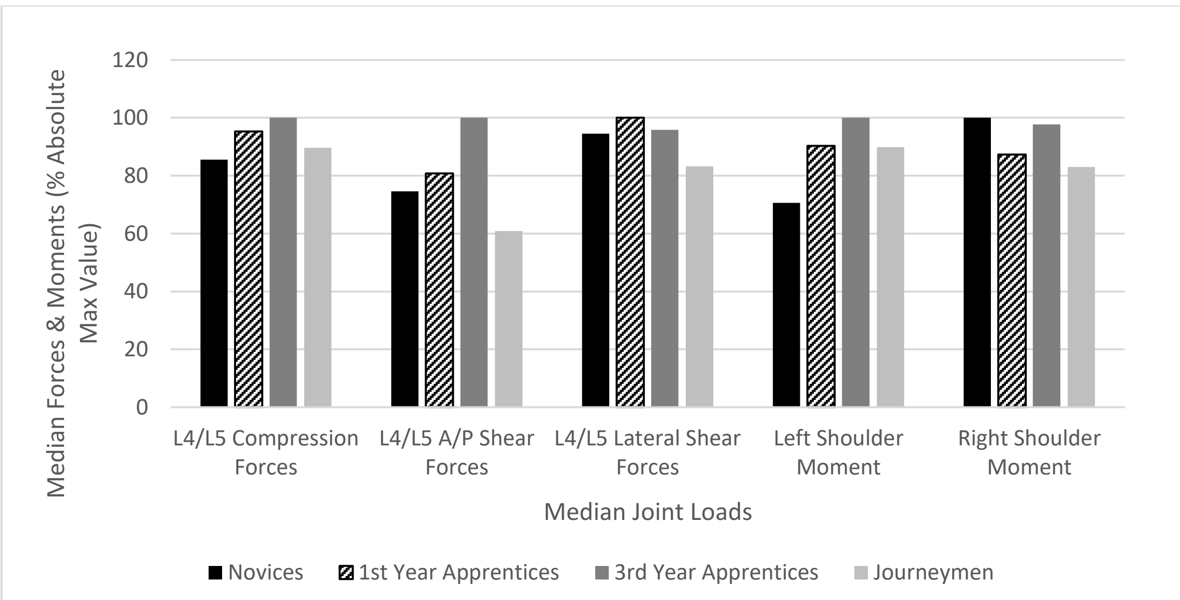


Figure 24: Median Joint Loads by Experience Group

Overall, both the novice and journeyman group are the safest in terms of critical joint loads at the low back and shoulder. Novices had significantly lower loads only in the case of mean L4/L5 compression forces, but it was only by 4%. However, journeymen are not only one of the safest groups, but also the most productive, where in comparison, novices rank last in terms of productivity out of the experience groups (Ryu et al., 2020a). The 3rd year apprentices had the highest body loads and were significantly higher in terms of L4/L5 compression than all other groups and higher left shoulder moment than novices. To determine the desirable and undesirable elements of kinematics in masonry, it will help to focus on the expert journeyman group as the model for both safe and productive behaviour, the novice group for safe behaviour, the 3rd year apprentice group as the primary model for unsafe behaviour and the 1st year apprentice group as a secondary model for less safe behaviour.

There was a significant interaction effect of experience group and course height on mean L4/L5 compression forces (Figure 25). Within each course height, the order of magnitude of mean L4/L5 compression forces repeated. At each course height, 3rd year apprentices had the highest forces, followed by 1st year apprentices, then journeymen and novices. Within each experience group, the total compression force decreased from the first course to the fifth course as the vertical height of the wall increased. The exception to this trend is in the 4th and 5th course where the compression force increased marginally in both 1st and 3rd year apprentices (3.3% and 1.7%, respectively). The increase in course height was typically associated with less flexion and other postural factors that contribute to higher compression forces. Therefore, not only are 3rd and 1st year apprentices associated with unsafe postures, the 1st and 2nd course of the wall would also be associated with more unsafe movement patterns. Furthermore, the differences in compression among the experience groups were more pronounced at course 1, that which caused the highest body loads.

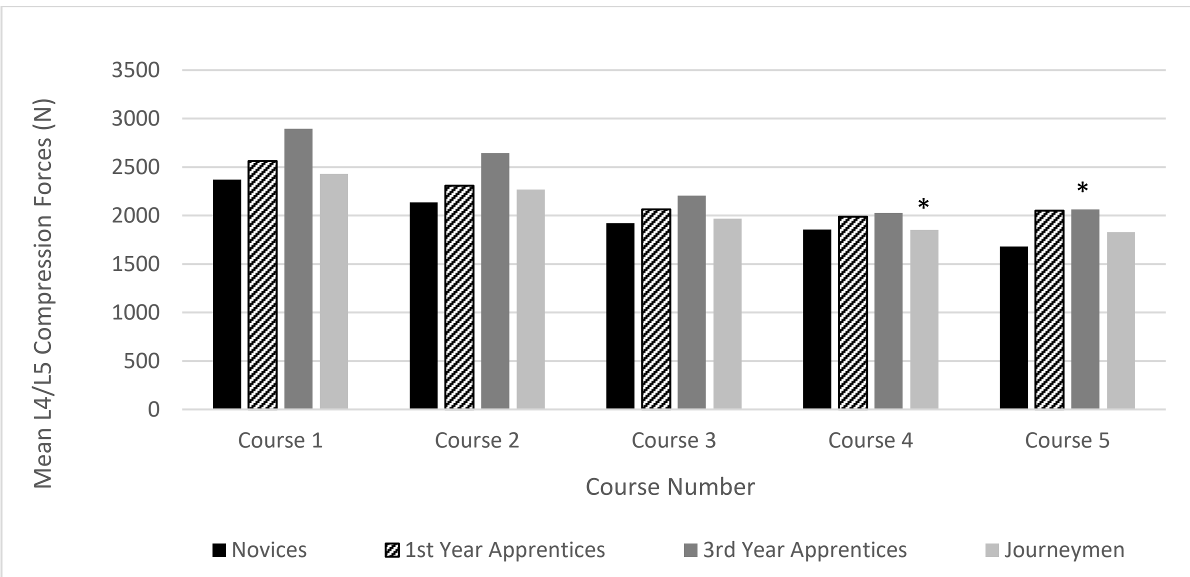


Figure 25: Interaction Effect of Experience Group and Course Height on Mean L4/L5 Compression Forces

**All columns significantly different from one another except for the columns indicated by the asterisk.*

At the second course, 3rd year apprentices had higher compression forces than both novices and journeymen at the first course (11.7% and 8.9%, respectively). In novices and journeymen, from the first to second course, L4/L5 compression forces decreased by 9.9% and 6.7%, showing that in this case, experience group had more of an effect than course height. Similarly, at the third course, 3rd year apprentices had higher compression forces (3.3%) than novices in the second course. However, this effect only occurred in these 2 cases and overall, the increase in course height had a greater impact on mean L4/L5 compression force than experience group. The greatest reduction in compression due to course height was 29.1% in novices from course 1 to 5, while the greatest reduction in compression due to experience group was only 18.2% from 3rd year apprentices to novices at course 1.

3.5 K-means Clustering

In addition to the statistical analysis, which identified the effect of experience group, and the interaction effect of experience group and course height on individual kinematic variables, a complementary analysis using K-means clustering was conducted to identify distinct working postures of masons. These postures were then categorized to provide additional insights into working techniques of various experience groups by studying whole-body postures rather than individual kinematic variables.

A subset of the data from 45 masons was analyzed using a k-means clustering algorithm that classified the masons' postures into 50 unique bins. An in-depth description of the k-means clustering process is described in Ryu et al. (17-2020b) and Alwasel et al. (18-2017b). Each of the bins was categorized as apprentice dominated, equal representation or expert dominated. Furthermore, the bins were classified as occurring during the pickup phase, the carrying phase or the laydown phase. Thirty postural variables and a 3D model of each pose was generated in MATLAB for all 50 bins. The 3D model was used in conjunction with the postural variables to create a visual description of the key features of the pose.

Using both the qualitative and quantitative data, poses were compared within and between experience groups at each of the lifting phases. Within experience groups, the poses were categorized by overall postural features e.g., squatting postures, stooping postures, or hip-hinging postures. For a finer comparison of motion strategies between groups, similar or similarly categorized postures were compared between groups where applicable e.g., inexpert squatting posture at pick-up compared to expert squatting posture at pick-up.

A final analysis was conducted on the results of the k-means clustering data. The k-means clustering process was reported in previous studies (Ryu et al., 2020b; Alwasel et al., 2017b). This analysis lays out the full results from the k-means clusters with regards to their postural implications for each of the experience groups, including an analysis of the different bins.

To enable objective comparison between expert and apprentice-dominated postures, each bin was further labelled according to the phase where it appears during a CMU lift, namely pick-up, transfer, or lay-down. These labels allowed us to deduce how different masons perform similar functions. The first 33% of frames were categorized as the pick-up phase, the last 33% of frames were categorized as the lay-down phase, with the rest of the frames between 33%-66% (inclusive) were categorized as the transfer phase. One cluster in the first 33% of frames was found to belong to the later stages of pick-up as participants rose from pick up and; therefore, was added to the transfer phase.

Next, we compared postures belonging to the same function by calculating their joint forces and moments using the 3D Static Strength Prediction Program (3DSSPP) (The Center for Ergonomics at the University of Michigan). Specifically, we compared the lumbar compression force and right shoulder and left shoulder joint moments, which are the critical joints during the CMU lifts under study.

Each of the clusters were represented with the closest posture from one of the participants. Where the exact frame extended beyond the total lifting frames, the last lifting frame was used as representative. Narrow stances were determined as <10% of height, shoulder-width stances were defined as between 10-20% height and wide stances were stances >20% height.

The k-means postures were analyzed by lifting phase and group type. Furthermore, for each expert dominated posture classification, a side-by-side comparison of the respective expert posture classification with the most similar inexpert posture was conducted.

The clustered postures were classified as distinctive to experts or apprentices by assessing the proportion of expert and apprentice postures present in the population of each bin. Specifically, bins were categorized as:

- 'Expert-dominated' where more than 65% of the postures belonged to experts.
- 'Apprentice-dominated' where more than 65% of the postures belonged to apprentice masons.
- Otherwise, the bins were labeled as 'similarly represented'. We hypothesize that those clusters represent postures common to human locomotion and the trade.

The proportion of expert and apprentice postures in each cluster is shown in Figure 26. Interestingly, expert postures were limited to 10 clusters out of all 50 clusters. In contrast, apprentice postures were present in most clusters. There were 24 apprentice-dominated clusters. This finding indicates that expert masons adopt a limited set of motions when performing repetitive lift tasks. At the same time, apprentices appear to utilize more complex and varied lift techniques when carrying out the same tasks.

Two clusters (5 and 46) were almost exclusively populated by experts and ten clusters (3, 10, 15, 19, 25, 32, 39, 40, 47, and 48) were almost exclusively populated by apprentices. Sixteen cluster histograms had similar proportions of expert and apprentice postures, for example cluster 11 was populated by 48% of expert and 52% of apprentice postures. These results are in accord with our previous conclusion that expert masons adopt a distinctive and simple set of work postures and motion pattern different from those of apprentice masons (Alwasel et al., 2017b).

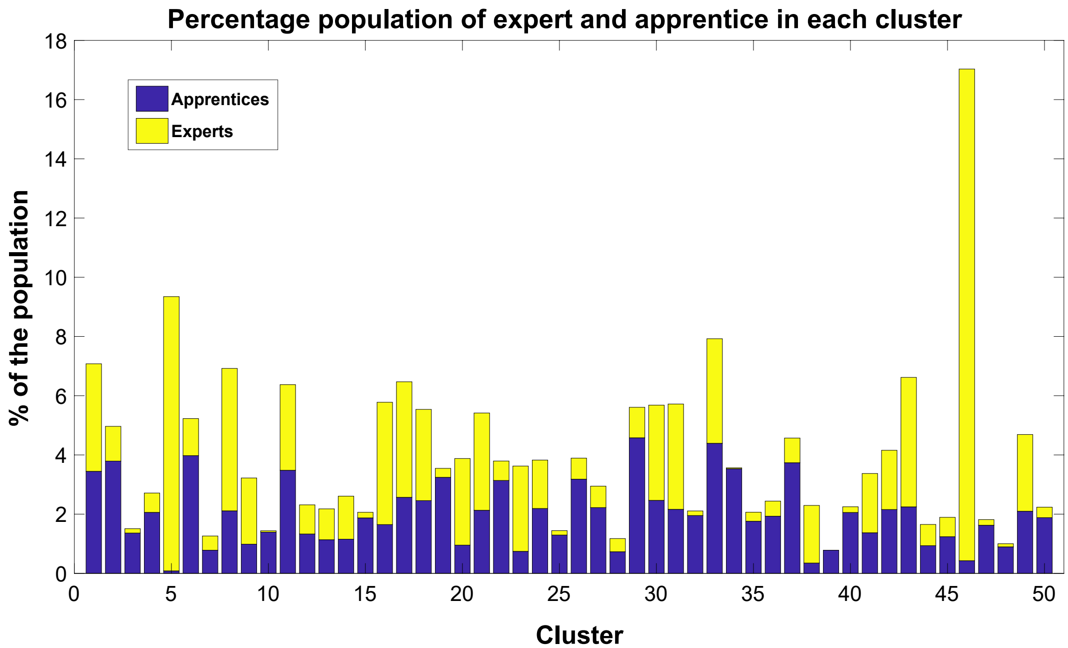


Figure 26: Posture Clusters Obtained from K-means Clustering

3.5.1 Relationships between Posture and Function

Examining the postures of the identified clusters, we found that they fall into five broad categories. Upright standing postures are primarily characterized by an upright trunk and minimal hip flexion. Those postures where the trunk is positioned in order to bring the centre of mass backward are labelled as 'leaning back'. In contrast, bending postures are characterized by forward trunk placement either via increasing the rounding at the lumbar spine, in stooped postures or via trunk and hip flexion in hip-hinged postures. The last posture, squat, is characterized by large hip and knee flexion angles. Table 10 classifies into these categories apprentice-dominated, similarly represented, and expert-dominated postures adopted to undertake the three phases of CMU lifts.

Table 10: Postures Adopted to Carry Out the Three Phases of CMU Lifts

Phase	Cluster	Standing		Bending		Squat	Total
		Upright	Leaning back	Stooped	Hip-hinged		
Pick-up	Apprentices	1	0	1	1	0	3
	Similarly Represented	1	0	0	0	0	1
	Experts	0	0	1	0	1	2
Transfer	Apprentices	0	2	2	1	1	6
	Similarly Represented	4	0	2	0	0	6
	Experts	0	0	1	1	0	2
Lay-down	Apprentices	4	2	2	5	2	15
	Similarly Represented	1	1	1	4	2	9
	Experts	2	0	0	2	2	6

3.5.1.1 Pick-Up Phase

Six of the identified clusters belonged to the pick-up phase, three of these were apprentice-dominated, two were expert-dominated, and the remaining cluster was similarly represented. Experts and apprentices adopted an upright similarly represented posture to pick-up CMUs from the top of the pile. Differences in posture appeared as participants bent and squatted to pick up CMUs further at lower heights. The single stooped expert-dominated posture was symmetric while a stooped and a hip-hinged apprentice-dominated postures showed evidence of asymmetry (axial rotation or side bending) in the frontal plane as can be seen in Figures 27 and 28. The aforementioned similarly represented posture involved asymmetry (axial twist) as well, but trunk flexion, in that case, was minimal resulting in lower risk exposure compared to the apprentice-dominated stooped postures. To reach down to the lower tiers, the experts also maintained a neutral spine in a squat posture, Figure 28.

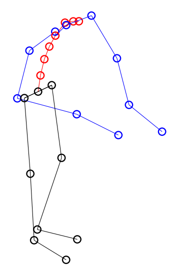
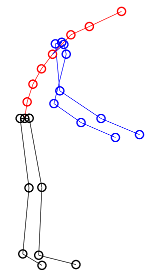
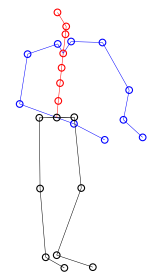
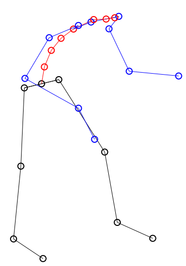
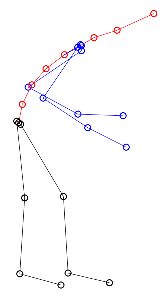
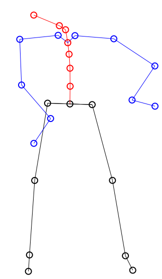
<table>
<tr><td>Cluster</td><td>Perspective view</td><td>Sagittal view</td><td>Frontal view</td></tr>
<tr><td>Cluster #48</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>Apprentice</td></tr>
<tr><td>Laydown Course 2</td></tr>
<tr><td>Cluster #9</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>Expert</td></tr>
<tr><td>Laydown Course 2</td></tr>
</table>

Figure 27: Comparison Between Expert and Apprentice Stooped Postures During the Pick-Up Phase

Apprentice-dominated postures had either a narrow stance, in the case of the stooped posture, or anterior/posterior stagger with the distance between the ankle joints reaching up to 20% H in the hip-hinged posture and 14% H in the upright posture. In contrast, expert postures had a shoulder-width or wide stance and minimal anterior/posterior stagger of the feet in addition to some knee flexion. Experts also minimized shoulder flexion and held the CMU closer to the body at a distance of 5-13% H anterior to body, measured from the hip joint center to the wrist joint center in the sagittal plane, compared to a distance of 14-18% H for apprentices, when the CMU was close to ground. On the other hand, apprentices and experts, in the similarly represented posture, placed the CMU farther away from the body, at distances of 21% H anterior to the hips and of 12% H lateral to body median, while holding it at higher levels.

<table>
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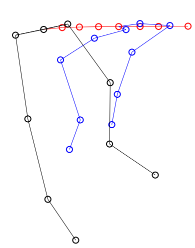
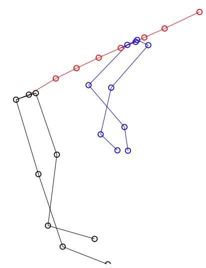
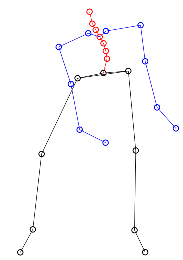
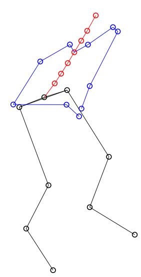
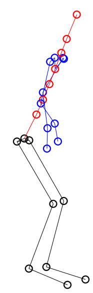
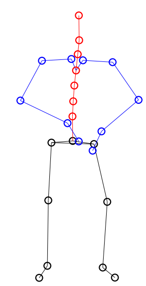
<tr><td>Cluster #3</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>Apprentice</td></tr>
<tr><td>Laydown Course 4</td></tr>
<tr><td>Cluster #38</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>Expert</td></tr>
<tr><td>Laydown Course 4</td></tr>
</table>

Figure 28: Comparison Between Expert Squat Posture and Apprentice Hip-Hinged Posture During the Pick-Up Phase

3.5.1.2 Transfer Phase

Fourteen of the identified clusters belonged to the transfer phase; six of those postures were apprentice-dominated, six were similarly represented, and two were expert-dominated. Four similarly represented upright posture were used to transfer CMUs to the to the top two layers of the standard wall (courses 4 and 5). One similarly represented stooped posture was used to transfer CMUs to the lower course (3), while the other was used in the initial stages of the transfer phase for CMUs destined to course 4.

Within the apprentice-dominated postures, two were leaning back, three were stooped or hip-hinged, and one was squat. Apprentices leaned back at the knees to counterbalance the CMUs load while transferring them to courses 4 and 5. Conversely, they deployed two hip-hinged and one stooped posture for the lower course heights (2 to 3). Similarly, the two expert-dominated postures, one stooped and one hip-hinged, and were adopted to transfer CMUs to the same courses (2 and 3).

Most expert and apprentice-dominated stooped and hip-hinged postures had shoulder-width or wide stances (15-30% H), minimal shoulder flexion (<25°), and held the CMUs close to body (<19% H anteriorly) at or just below hip height. These overarching characteristics represent common good practice to transfer CMUs to lower course. The main difference between the expert and apprentice hip-hinged postures, Figure 29, was that experts pushed their hips back by flexing their hips and knees between 31° and 36°, thereby helping to balance the forward moment exerted by the CMU weight. In addition, one of the apprentice-dominated postures had severe spine asymmetry.

The only transfer phase cluster to demonstrate a squat posture was apprentice-dominated. They used it in the transfer of CMUs destined for course 1.

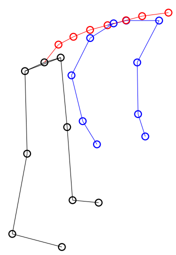
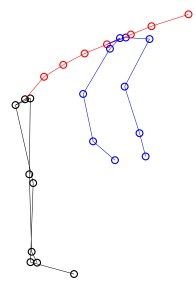
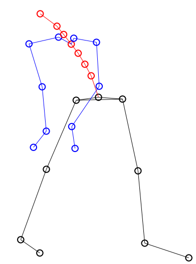
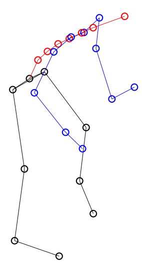
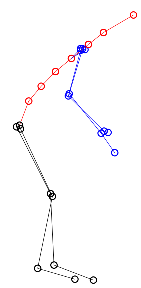
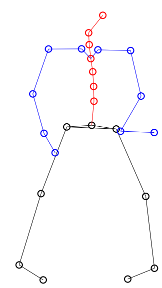
Cluster	Perspective view	Sagittal view	Frontal view
Cluster #32			
Apprentice			
Laydown Course 2			
Cluster #23			
Expert			
Laydown Course 3			

Figure 29: Comparison of an Apprentice and an Expert Hip-Hinged Posture in the Transfer Phase

3.5.1.3 Lay-Down Phase

Thirty of the identified clusters belonged to the lay-down phase; fifteen of those postures were apprentice-dominated, nine were similarly represented, and six were expert-dominated. A similarly represented posture leaned-back during lay down of CMUs at course 5. This posture allowed masons to balance the CMU mass, lifted at chest height with outstretched arms, against the mass of a leaning-back torso. Another similarly represented posture was upright with a torso twist angle to lay down to the left at course 3. Four of the similarly represented postures were hip-hinged. They employed varying degrees of hip and knee flexion to lay down CMUs at courses 1 to 3. Two similarly represented squat postures were employed to lay-down CMUs at course 2. Finally, a stooped posture, Figure 30, with severe rounding of the lumbar spine as well as torso, hip and knee flexion was employed to lay down at course 1. This posture had the highest lumbar compression force among all identified clusters. Although it was shared among experts and apprentices, it is a poor posture where the ergonomic demands of laying at the lowest course were exacerbated by large neck flexion (43°), neck right-side bending (-13°), severe rounding of the lumbar spine, and large forward torso flexion (93°) and side bending (94°).

<table>
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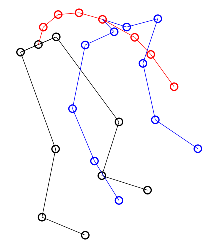
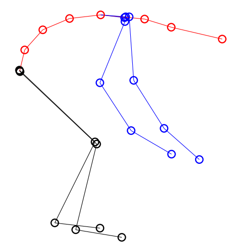
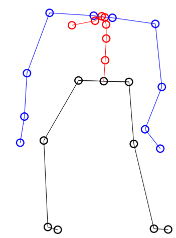
<tr><td>Cluster #11</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>Similarly Represented</td></tr>
<tr><td>Laydown Course 1</td></tr>
</table>

Figure 30: Three Views of an Unsafe Similarly Represented Stooped Posture Used to Lay-Down CMUs at Course 1

Experts and apprentices also used distinct standing postures to lay down CMUs at courses 4 and 5. These included four apprentice-dominated upright postures, two apprentice-dominated leaning-back postures and two expert-dominated upright postures. In addition, apprentices used two stooped postures to lay down at course 4. The only difference among these postures was that experts minimized torso flexion and rounding of the spine compared to small but finite positive torso flexion (in apprentice-dominated upright postures), Figure 31, negative torso flexion (in apprentice-dominated leaning-back postures), Figure 31, and rounding of the spine (in apprentice-dominated stooped postures). A more salient difference is that experts stood further away from the CMUs at an anterior distance of 25-26% H than the apprentices where the anterior distance was less than 20% H in all, but two of the upright postures, in the apprentice-dominated postures.

<table>
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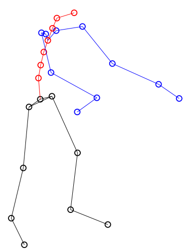
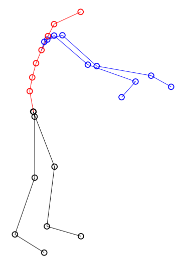
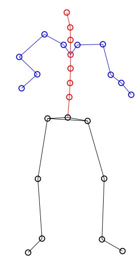
<tr><td>Cluster #2</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td></tr>
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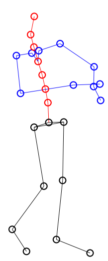
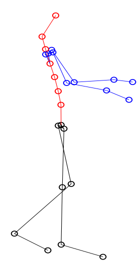
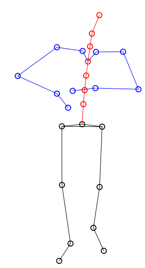
<tr><td>Laydown
Course 5</td></tr>
<tr><td>Cluster #15</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td></tr>
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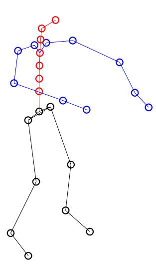
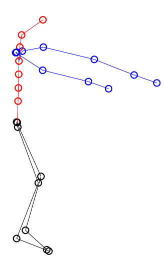
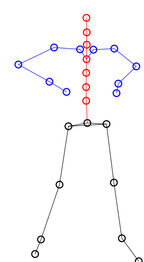
<tr><td>Laydown
Course 4</td></tr>
<tr><td>Cluster #46</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>Expert</td></tr>
<tr><td>Laydown
Course 5</td></tr>
</table>

Figure 31: Comparison Among Apprentice-Dominated Upright and Leaning-Back Postures and an Expert-Dominated Upright Posture During the Lay-Down Phase

Five apprentice-dominated hip-hinged postures involved large trunk flexion angles and, in some cases, an additional risk factor of trunk asymmetry with apprentices leaning to one side with their hips while laying the CMU at the other side, Figure 32. These postures were employed to lay down CMUs at courses 1 to 3. Experts leaned forward and had a narrow stance (≤10% H). In both of their postures, the hips were pushed back and to one side to balance both the CMU and trunk side bending on the contralateral side.

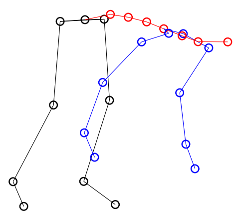
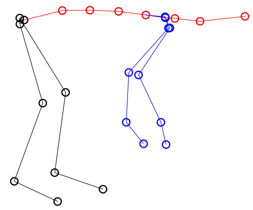
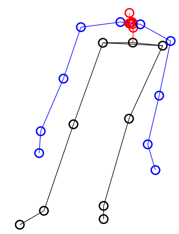
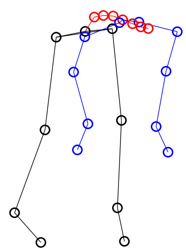
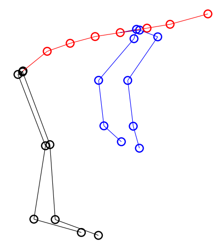
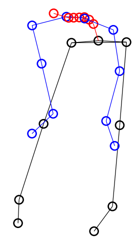
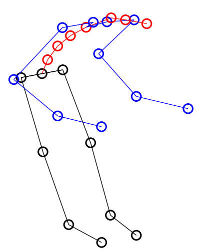
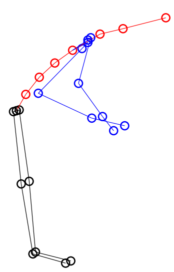
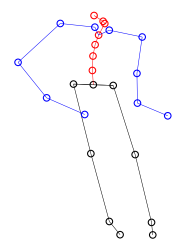
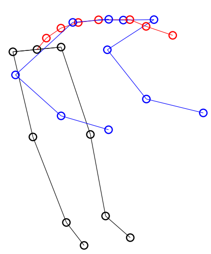
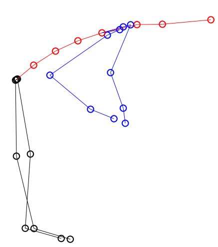
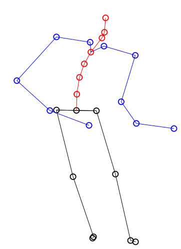
Cluster	Perspective view	Sagittal view	Frontal view
Cluster #10 Apprentice Laydown Course 1			
Cluster #22 Apprentice Laydown Course 1			
Cluster #8 Expert Laydown Course 3			
Cluster #33 Expert Laydown Course 2			

Figure 32: Comparison Among Apprentice and Expert Hip-Hinged Postures During the Lay-Down Phase

Apprentices adopted two squat postures exclusively to lay down at course 1 and 4. Experts adopted a squat posture to lay at course 2 and another squat posture to lay at course 3. In contrast to apprentices, both expert postures featured wide stances, hips pushed away from the wall, and a neutral spine. Figure 33 compares a squat apprentice posture and an expert posture.

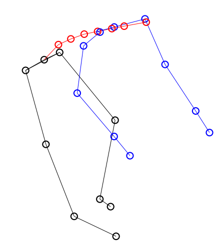
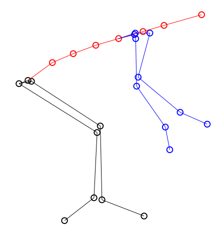
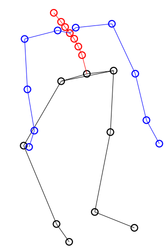
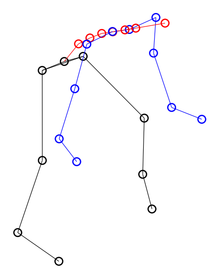
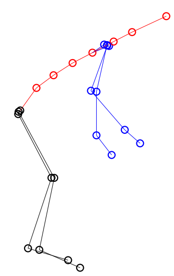
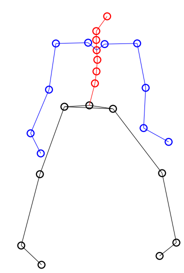
Cluster	Perspective view	Sagittal view	Frontal view
Cluster #50 Apprentice Laydown Course 1			
Cluster #43 Expert Laydown Course 3			

Figure 33: Comparison Between an Apprentice and an Expert Squat Posture During the Lay-Down Phase

3.5.2 Joint Loads

Average lumbar compression force for apprentice-dominated, similarly represented, and expert-dominated postures during the pick-up, transfer, and lay-down phases are shown in Figure 34 grouped into the five postural categories described above. The lumbar compression force varies with experience, posture, and lift phase. Both types of standing postures, upright and leaning-back, have lower lumbar compression forces compared to other postures irrespective of the lift phase or experience level. Similarly, lumber compression forces were within or close to the safe (action) limit, ranging from 1838.3 N to 3337.3 N, irrespective of posture and experience level, except for one apprentice-dominated hip-hinged posture that was significantly in excess of that limit at 4229 N. Those results shows that the critical points in CMU lifts occur during the pick-up and lay-down phases.

In contrast, ergonomic risks were present in the pick-up and lay-down phases. The apprentice-dominated bending postures at pick-up was more hazardous, with the lumbar compression force at 3932.7 N (stooped posture) and 3774.8 (hip-hinged posture) above the action limit at 3433 N (NIOSH, 2014), than the corresponding expert posture with the compression force at 3192.9 N (stooped posture). Experts solely employed squat postures at pick-up phase, which had the lowest lumbar compression force (1237 N) in this phase.

Similarly, expert-dominated bending and squat postures used to lay-down CMUs at courses 2 and 3 had lower lumber compression forces compared to those of apprentice-dominated and similarly represented postures. However, the bending postures used to lay-down CMUs at course 1, lacked an expert-dominated posture. Moreover, the similarly represented stooped and hip-hinged postures used to lay-down CMUs at course 1 had lumbar compression forces in excess of the safe limit. In fact, the similarly represented stooped posture used to lay-down CMUs at course 1 had the highest lumbar compression force among all 50 identified postures at 6278.4 N.

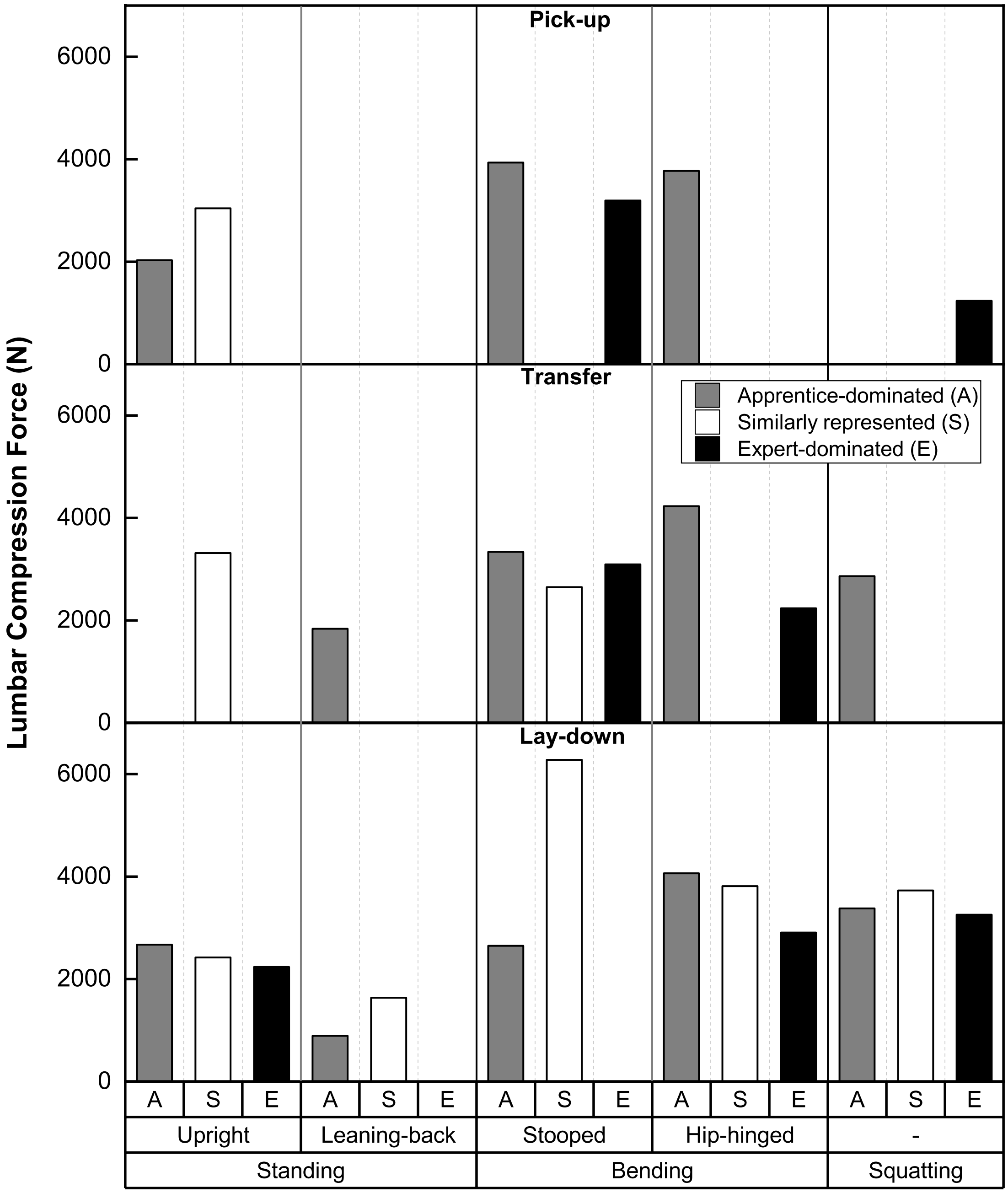


Figure 34: Average Lumbar Compression Force for Each Postural Category

Average shoulder joint moments, Figure 35, also show several instances of variation among different experience groups for similar functions. This was expected given the large range of motion and possible positions the arms and torso can take to perform the same function. However, the observed trends were mirrored for the right and left shoulders except for some of the apprentice-dominated and similarly represented bending postures. This is expected since all the CMUs lifts in this study were two-handed. It is also good practice to balance the load between the two arms.

The standing postures had the highest shoulder joint moments across all experience groups and lift phases. These postures had in common raised arms, close to the shoulder-level, and CMU placement father away from the body. In contrast, bending and squat postures had lower shoulder joint moments in all lift phases and irrespective of experience. Specifically, the shoulder joint moments of stooped and squat postures were 40% of the moment in standing postures, and those of hip-hinged posture were 20% of the shoulder moment of the standing postures. This is expected since those postures are associated with placing the CMU and a closer distance to the body.

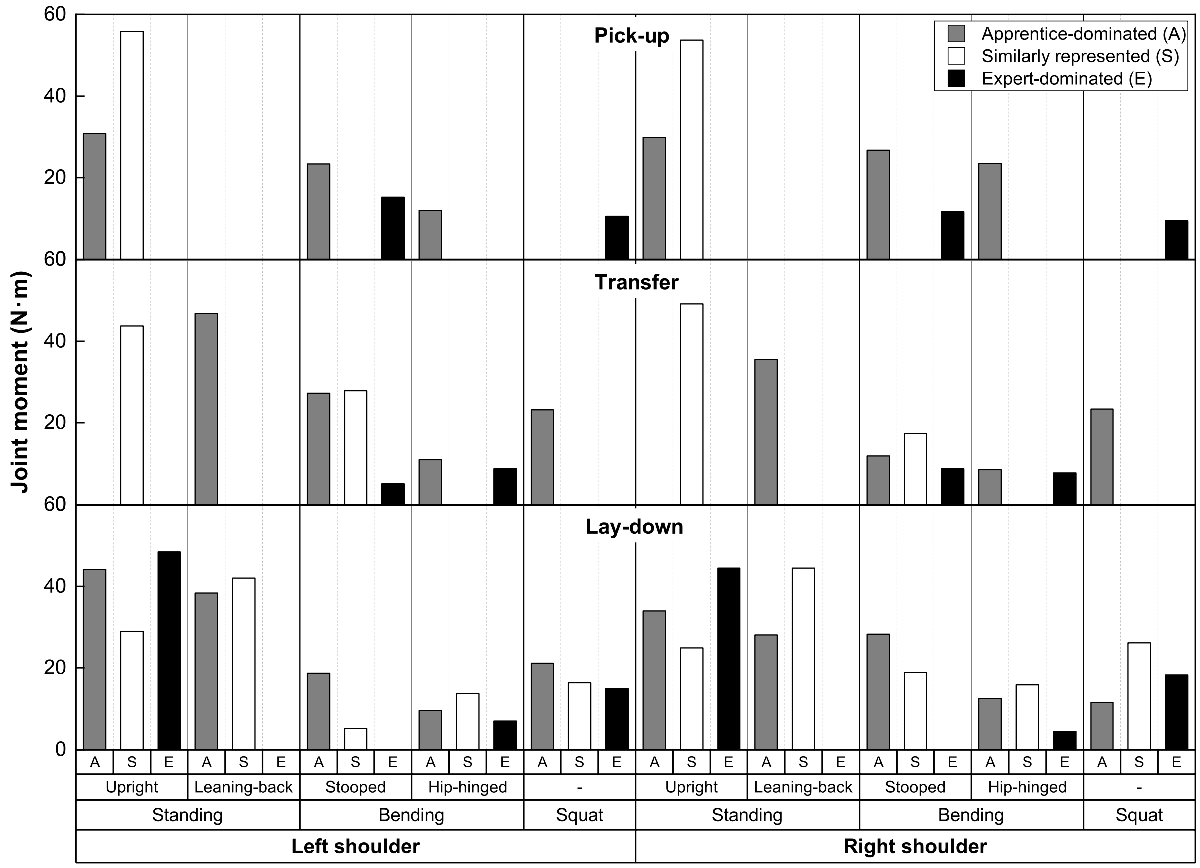


Figure 35: Average Right and Left Shoulder Joint Moments for Each Postural Category

The average joint loads for each of the postural categories, represented in Figures 34 and 35 are presented numerically in Table 11.

Table 11: Average Joint Loads for Each Postural Category

Phase	Cluster	Joint Load (N/Nm)*	Standing		Bending		Squat
			Upright	Leaning-back	Stooped	Hip-hinged	
Pick-up	Apprentices	LCF	2025.2	0	3932.7	3774.8	0
		L-ShM	30.8	0	23.4	12.0	0
		R-ShM	29.9	0	26.7	23.5	0
	Similarly represented	LCF	3042.9	0	0	0	0
		L-ShM	55.8	0	0	0	0
		R-ShM	53.7	0	0	0	0
	Expert	LCF	0	0	3192.9	0	1237.0
		L-ShM	0	0	15.3	0	10.6
		R-ShM	0	0	11.7	0	9.5
Transfer	Apprentices	LCF	0	1838.3	3337.3	4229.0	2864.8
		L-ShM	0	46.8	27.3	11.0	23.2
		R-ShM	0	35.5	11.9	8.5	23.4
	Similarly represented	LCF	3315.1	0	2650.4	0	0
		L-ShM	43.7	0	27.9	0	0
		R-ShM	49.1	0	17.4	0	0
	Expert	LCF	0	0	3089.3	2237.8	0
		L-ShM	0	0	5.1	8.7	0
		R-ShM	0	0	8.7	7.7	0
Lay-down	Apprentices	LCF	2672.3	892.3	2647.4	4060.7	3380.7
		L-ShM	44.1	38.3	18.7	9.6	21.2
		R-ShM	34.0	28.1	28.3	12.5	11.6
	Similarly represented	LCF	2418.9	1427.1	6278.4	3815.7	3729.8
		L-ShM	29.0	42.0	5.2	13.7	16.4
		R-ShM	24.9	44.4	18.9	15.9	26.1
	Expert	LCF	2238.4	0	0	2906.1	3254.8
		L-ShM	48.4	0	0	7.0	14.9
		R-ShM	44.4	0	0	4.5	18.3

* LCF: Lumbar compression force (N); L-ShM: Left shoulder moment (Nm); R-ShM: Right shoulder moment (Nm)

3.5.3 Discussion

This analysis introduced an automated posture clustering method and deployed it to identify the proper working postures that workers develop as they gain experience. The method utilizes whole-body motion data and a *k*-means clustering algorithm to identify the most frequent postures in an ensemble of CMU lifts. Motion data were collected from forty-five masons with different experience levels while they carried out an indoor masonry task, namely completing a lead wall using 45 standard CMUs. Six of those participants were experts with more than 20 years of experience while the rest were apprentices at various stages of their training.

The identified postures were classified into three categories: expert-dominated, similarly represented, and apprentice-dominated by evaluating the population belonging to the expert and apprentice groups in each cluster. The identified postures were also labelled, based on their frame numbers, as a pick-up, transfer, and lay-down posture. Labelling the lift phase enabled objective comparison among clusters corresponding to the same function. These analytical methods have significant advantages over the corresponding manual observation methods, typically employed for onsite work assessment, where it is almost impossible to accurately obtain and compare postures appearing during continuous body motion. Moreover, visualization of the clustered postures allows for an intuitive understanding of the differences in techniques undertaken to carry out the same function.

The 50 identified clusters were composed of 24 apprentice-dominated, 16 similarly represented, and 10 expert-dominated clusters. We found that experts dominated some clusters and were represented heavily enough in other clusters to render them similarly represented, despite their small number compared to apprentices. These findings show lower variation in postures that experts favour. They reinforce the notion that experts adopt characteristic work techniques compared to apprentices. Two theories explain apprentice variability as either an integral part to skill learning or a consequence of attrition. The first theory posits that the apprentice group has not learned best techniques yet and is sampling a wide variety of techniques. In a complex systems approach, increased variability in the learning stage is considered critical to develop functional variability and converge on an optimal technique (Bartlett et al., 2007; Lee et al., 2014c; Selinger et al., 2015). Another theory is that a variety of postures are used due to a lack of training on safe handling and work techniques, those who frequently use the most demanding postures eventually leave the workforce due to injury, never becoming experts. The second theory correlates well with occupational injury reports in the construction industry. Specifically, the numbers of injuries increased until it reached a maximum for those with 5 years of experience and decreased thereafter (STATISTICS, 2014).

To investigate how different masons perform similar functions, the clustered postures were grouped into the three lift phases: pick-up (7 clusters), transfer (13 clusters), and lay-down (30 clusters). We further classified those postures into five categories describing the body configuration, namely upright, leaning-back, stooped, hip-hinged, and squat. Standing postures were commonly adopted by apprentices and experts to pick up CMUs from the top tiers of the piles, to transfer them, and to lay them down at the higher courses of the wall (4 and 5). These postures were characteristic of CMU handling at or above waist level. They had lower lumbar compression forces, below the safe (action limit), indicating that ergonomic stresses were lower for this working height, which, in turn, minimizes differences between apprentices and experts. These results suggest that no ergonomic intervention is required to prevent lower back injuries while handling standard CMUs at or above the waist level. This conclusion is in agreement with findings that the optimal lifting height is above the knee and that low lifting heights are associated with increased risks of MSDs (Ngo et al., 2017).

Differences between experts and apprentices arose in bending postures to pick up CMUs. The most striking was the difference in the straight back posture both groups adopted to pick

CMUs from the pile's lower tiers, Figure 28. Apprentices combined a neutral spine with a hip-hinged posture resulting in a deadlift with large trunk flexion and exposing the lumbar spine to significant loads. In contrast, experts combined a neutral spine with a squat posture that decreased trunk flexion and lumbar spine load, which was one-third of the load in the apprentice-dominated posture. Similarly, while apprentices and experts used stooped postures to pick up, the apprentice-dominated posture was more hazardous with a lumbar compression force above the safe limit. Experts also improved their medial-lateral balance while picking up near a pile by adopting a shoulder-wide or wider stance while minimizing the anterior-posterior stagger of their feet. Therefore, is an obvious advantage in training apprentices to follow expert practice in pick-up from lower tiers.

In the transfer phase, expert-dominated bending postures resulted in lower lumbar compression forces than those of apprentice-dominated postures. While there is space to reduce ergonomic risk of apprentices in the transfer phase, it is not as urgent as the case in pick-up and lay-down phases.

Expert-dominated postures had the lowest lumbar compression forces in the lay-down phase. Experts also improved their medial-lateral balance while laying down near a wall by adopting a shoulder-wide or wider stance while minimizing the anterior-posterior stagger of their feet. There are; therefore, ergonomic lessons for apprentices to learn for experts particularly in laying down CMUs below the waist level, courses 2 and 3. However, at the lowest course, course 1, both experts and apprentices used poor ergonomic postures resulting in elevated lumbar compression forces well in excess of the safe limit. Although similarly represented postures typically were indicative of good workmanship under low or moderate ergonomic demands, that was not the case here. Therefore, there is a need for ergonomic intervention to help masons to lay down CMUs at the lowest course of a wall safely.

Previous studies using partial (Alwasel et al., 2017a) or extended (Ryu et al., 2020a) datasets compared reported that working methods adopted by expert masons can help reduce occupational injuries and improve productivity. The aim of the present analysis was to identify those proper working postures by investigating the distinctions between the working postures of expert masons and less experienced masons. The methods and findings reported here play an important role in:

1) providing insights for methods to objectively compare working postures of experts and apprentices

2) identify and convey those expert work methods to trainees and trainers in highly detailed and visual form that can be used directly as training material.

3.6 Recommendations

All three analyses had complementary roles, and each provided some insight into how masons' techniques influence joint forces. The results of the analyses all have implications with respect to recommendations for best lifting practices. The predictor screening determined which kinematic variables have the greatest contribution to peak joint loads, while the statistical postural analysis revealed which individual kinematic variables were significantly different between experience groups. The k-means clustering analysis revealed which whole-body postural categories were dominated by apprentices and which were dominated by experts.

The predictor screening analysis revealed that in order to have the greatest potential for impact, training should target the following postural variables first: trunk, neck, hips, shoulders, vertical and anterior CMU carrying distance and stance distance. The statistical analysis of the postures by experience group revealed more detailed insights into undesirable and desirable postures during a standard wall build, which is presented in Table 12.

Table 12: Summary of Recommendations Based on Postural Analysis

Lifting Attribute	Undesirable Postures	Desirable Postures
Neck Flexion and Extension	Excessive neck flexion Especially 3rd year apprentices	Minimal neck flexion Neutral neck position Some extension acceptable at course 1 (< ~6° extension)
Torso Flexion	High torso flexion, especially at course 1	Avoid excessive torso flexion Maintain a neutral spine position
Torso side bending	Avoid unnecessary torso side bending especially at higher courses (3-5) Especially 1st year apprentices	Side bending is a strategy of journeymen at lower courses
Torso Twist	Avoid twisting at the torso especially in flexed positions at the lower courses (1-3) Especially 1st year apprentices	Twisting more acceptable if spine is not-flexed Torso twisting is a strategy of journeymen at higher courses
Hip Flexion	Insufficient hip flexion Using mobility of the spine rather than hips	High degrees of hip flexion Use hip mobility over spine mobility Transfer load to hips rather than spine Increase amount of hip flexion to a greater amount at especially at lower courses (1-3)
CMU Carrying Distance	Carrying the CMU farther by 1-5% of height is not always worse However, one should still avoid holding CMU excessively far from the body which may cause compensatory postures at other parts of the body	Journeymen carry the CMU father in front of themselves at lower course heights compared to higher course heights Journeymen carry the CMU typically farther anteriorly compared to other groups (at course 1-4) Avoid carrying the CMU farther than 25% of height in front of you

The k-means analysis revealed that at higher course heights, there are less differences between inexpert and expert groups; however, poor postures are more likely to be adopted by the inexpert group. At lower course heights there are more likely to be differences between groups depending on experience level. Laying blocks at lower course heights is not only more demanding due to task constraints, but there is also more potential for inexperienced masons to adopt more at-risk postures. Therefore, training should target these higher risk postures. Stooped positions with rounding at low back are dangerous and should be avoided. Hinging at the hips, squatting, or using a deadlift strategy with a neutral spine should be encouraged. The key is to maintain neutral spine while bending by utilizing mobility at the hips and knees, rather than the spine. One of the key takeaways from the k-means clustering analysis was also that experts adopt different postures at different phases of the lift, and that there is no singular correct technique in experts, despite experts adopting a more limited selection of postures. This finding is in line with previous recommendations on manual handling training that encourages a de-emphasis on a singular safe technique and instead suggests training should focus on allowing trainees to choose the appropriate action based on the scenario (Denis et al.,2020). The training implications of the k-means analysis is presented in Table 13.

Table 13: Summary of Recommendations Based on K-means Clustering Analysis

Lifting Attribute	Undesirable Postures	Desirable Postures
Trunk Extension	Back extension or leaning back Frequently seen with rounded spines and lots of neck flexion Typical in inexpert groups, at higher course heights (4-5) in transfer or lay-down phase	Stand upright and stack shoulders over hips Maintain a neutral spine Brace core or bring CMU closer to body if needed
Spine Curvature	Stooped postures Rounding at lower back Especially at lower course heights (1-3)	Try to maintain a neutral spine Squat or deadlift hinge Hinge at hips and/or knees rather than at the lower spine Hip flexion is key
Trunk Asymmetry	Avoid twisting, especially in a flexed position Avoid side bending if possible	Position hips towards desired direction, or use hips to balance Move/twist on feet rather than with spine
Neck Flexion and Bending	Severe neck flexion or side bending	Maintain a neutral neck position and minimize flexion Minimal flexion or some extension when bending over Deadlift may be better at low course heights (1-2) to position spine to see working area without additional neck flexion

Stance Width	Narrow stances	Shoulder-width to wide stance Especially when bending over
CMU Carrying Distance	Positioning body too close to CMU	Position body farther away from the wall during lay down by taking a step back or holding the CMU closer Hold CMU within a reasonable range while lifting
Hip Flexion	Not enough hip flexion Bending at the spine rather than the hips	Increase hip flexion Use hips for bending strategies
Side Leaning	Avoid using spine to twist and balance CMU to one side	Utilizing hips when bending and balancing Lean with hips to reduce side bending at spine Narrow stance in leaning strategy Possible strategy at mid-height courses (2-3) but not at lowest course (1) Note: Try to maintain neutral spine in this position!

3.7 Proposed Framework

Key postural characteristics from expert masons' lifting strategies were analyzed and identified from experimental data (Sections 4.3-4.5). To establish clear guidelines for the enhanced training tool, these characteristics were compared to high-risk postures identified in the literature (Section 4.1). Consideration of the two led to a set of quantitative postural thresholds for at-risk movements and qualitative descriptions of desired movements.

The training tool implemented a buffer of +/- 5° around thresholds of 0° to allow for natural deviations about a neutral joint position. For a threshold to be exceeded, a joint angle must be held for a minimum of 3 frames. The thresholds for joint angles used in the training tool are displayed in Figure 36.

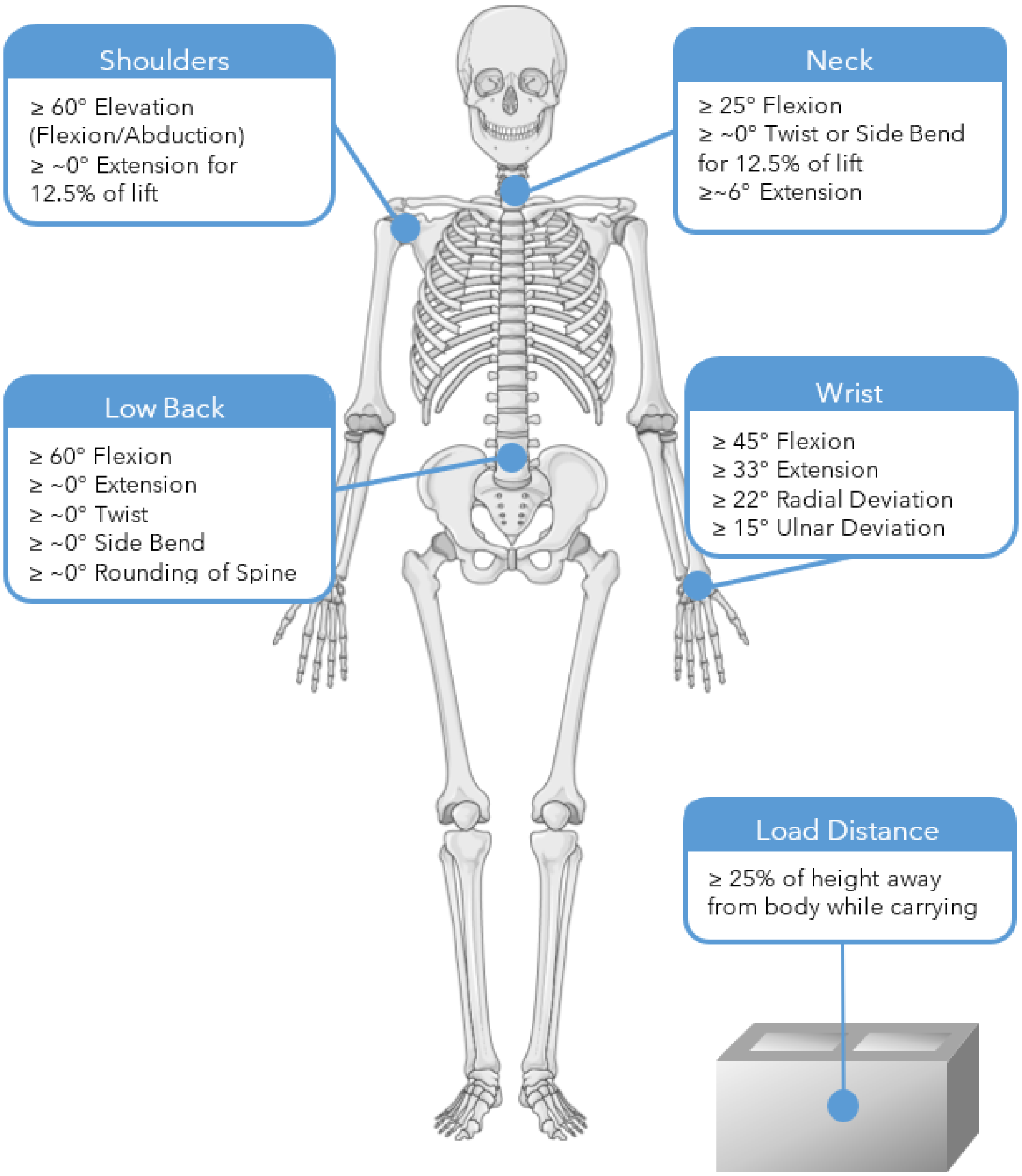


Figure 36: Quantitative Postural Thresholds Based on Kinematic Analysis and Review of Literature

3.8 Conclusions

Masonry workers face high physical demands and thus are more susceptible to MSDs. While previous research established that expert masons use different strategies to perform their work, while experiencing reduced joint loads and increased productivity, it was unclear which movement strategies they used. The results of this research describe the movement strategies experts use in comparison to inexpert groups (novices and apprentices). Through the analysis of expert techniques, the intrinsic movement knowledge of expert masons was translated into numeric joint thresholds and coaching feedback for a prototype training tool.

Chapter 4
Modeling Expert Behaviour[2]

4.1 Introduction

The quantification of injury risk is a complex challenge because injury risk is multifactorial. Musculoskeletal risk is affected by a variety of factors including individual traits (genetics, morphology, and psychosocial factors), biomechanical risk factors (force, repetition, duration and posture), and the integration of those factors acting on the soft tissues of the body (Kumar, 2001). Since individual risk factors will vary between workers, the best estimate of occupational demands will stem from the analysis of biomechanical exposures, namely force, posture, and time (i.e., repetition or duration). While repetition and external loads can often be easily measured, internal demands (e.g., joint forces or muscle requirements) and posture are harder to quantify without the appropriate tools.

To evaluate biomechanical exposures in construction, there are five main categorizations of methods: self-report, observational, direct measurement, remote-sensing and simulation-based methods (Wang et al., 2015). Self-report methods are useful for gathering subjective data but can be unreliable between individuals and inaccurate (Wang et al., 2015). These often take the form of checklists to report symptoms or risks. Observational methods are limited by lower correspondence with technical measures and lack of detailed continuous data (Takala et al., 2010). However, observation methods are one of the most practical methods used in the industry, due to a trade-off between overall accuracy with lower demands for time, cost, and expertise. Studies have also determined that observational methods are lack precision and are inaccurate for manual handling tasks, since these techniques often focus on postural categorization and neglect the influence of forces on the joints (Ryu et al., 2018). Quantitative measures also have more precision and sensitivity compared to observational methods regarding the classification or analysis of postures especially near bin boundaries (Andrews et al., 2008; Takala et al., 2010).

Quantitative data collection methods include the direct measurement of body motion, forces, and muscle activity. In laboratory studies, optoelectronic motion capture systems are considered the ‘gold standard’ for kinematic data collection (Kim and Nussbaum, 2013); however, these systems are often impractical for use in field studies. Inertial measurement units (IMUs) are more advantageous for use in working environments because they do not require a line of sight, and they are portable, lightweight, and low-cost (Bolink et al., 2016; Morrow et al., 2017; Robert-Lachaine et al., 2017). An acceptable level of accuracy and validity has been

[2] Part of this chapter is adapted from:

Ryu, J., **McFarland, T.**, Banting, B., Haas, C., and Abdel-Rahman, E. (2020). Health and Productivity Impact of Semi-Automated Work Systems in Construction. Automation in Construction, DOI: 10.1016/j.autcon.2020.10339

McFarland, T., Mahmassani, A., Ryu, J., Banting, B., Haas, C., and Abdel-Rahman, E. (2021, May 16-20). *Development and Implementation of Automated Apprentice Assessment Tool for Manual Handling Tasks in Masonry* [Paper presentation]. 14th Canadian Masonry Symposium (CMS), Montreal, CA.

reported for the measurement of kinematics with IMUs (Bolink et al., 2016; Morrow et al., 2017; Robert-Lachaine et al., 2017). Recent research in construction has presented methods to automate the classification of postures and the assessment of MSD risk using data from IMU systems (Chen et al., 2017; Valero et al., 2016; Yan et al., 2017b; Chen et al., 2014) or similarly, smartphone sensors (Akhavian and Behzadan, 2016; Nath et al., 2017). An alternative approach to direct measurement, is to estimate internal demands using muscular activity rather than postural and force assessments. Electromyography (EMG) can be used to assess relative muscle activity levels, the amount of time the muscles are active versus inactive (i.e., work-rest cycles), and muscular fatigue (Hagg et al., 2004).

Remote-sensing methods could be another avenue to collect onsite kinematic data; other researchers are developing marker-less camera systems for posture recognition of construction workers and ergonomic analysis (Yan et al., 2017a; Ray and Teizer, 2012).

Lastly, simulation-based methods can also be used to evaluate task demands, joint loads and internal forces without directly measuring a worker. In simulation-based methods, a digital human model can be incorporated into a virtual reconstructed environment to estimate the biomechanical loads that an operator might face during a prescribed task (Jayaram et al., 2006). This is advantageous to evaluate the potential impacts of workplace redesign without the costs and time of changing the physical environment. However, a disadvantage of this method is that the accuracy of the simulation depends on the accuracy of the inputs and the assumptions made by the model. Furthermore, humans have large variability in movement decisions and simulations cannot always accurately predict the way an individual may move in a complex environment or task (Reed et al., 2006). For example, while completing the same task (building a standard wall), expert masons moved in a significantly different way than apprentice masons, and consequently experienced lower joint loads and injury risk than apprentices (Alwasel et al., 2017a; Alwasel et al., 2017b). It was also identified that expert masons had less wasted motions and were more productive than the apprentices and novice workers (Alwasel et al., 2017b). Direct measurement may facilitate the capture of more detailed and nuanced information with respect to the real scenario, whereas simulation may miss these pieces.

Nevertheless, direct measurement and calculation of joint loads is inaccessible for a regular tradesman, foreman or instructor because it requires specialized and often expensive equipment, training, and expertise. Furthermore, just knowing the joint loads is insufficient without additional context for injury risk. There are a few methods in the literature that could provide this additional context.

The first is task-specific thresholds for acceptable lifting or manual handling loads. For example, the National Institute for Occupational Safety and Health (NIOSH) lifting equations (NIOSH, 1981), or the Liberty Mutual manual materials handling tables (Snook and Ciriello, 1991). However, these estimations of acceptable loads apply only to very rigid movement classifications of lifting and lowering etc. and would therefore exclude the variable movements involved in masonry tasks.

For forces at the low back, the industry standard is the NIOSH low back compression limits. This lifting equation was created in 1981, and since revised in 1993, as a method to determine acceptable weights for lifting in the workplace (NIOSH, 1981; Waters et al. 1993). The guidelines set by NIOSH are one of the most accepted thresholds for compressive loading in both biomechanics research and in the industry. The action limit is defined as the value under which workers are at little risk for low back injury; this is a conservative limit designed to protect approximately 99% of male workers and 75% of female workers (Nelson et al., 1981; NIOSH, 1981). Lifting loads above the action limit and below the maximum permissible limit represents increased risk for some workers, whereas lifting loads above the maximum denotes unacceptably high risk for many workers (Nelson et al., 1981; NIOSH, 1981; Waters et al., 1993). The action limit and maximum permissible limit are 3433 N and 6376 N, respectively (Marras, 2000; NIOSH, 1981).

For shear loading limits, most researchers agree that a maximum permissible limit of 1000 N, for fewer than 100 repetitions a day poses an unacceptably high risk to workers (Gallagher and Marras, 2012; McGill et al., 1998; McGill et al., 1997). However, for more frequent exposures, the original recommendation for an action limit of 500 N has since been challenged (Gallagher and Marras, 2012; McGill et al., 1998; McGill et al., 1997). Gallagher and Marras (2012) argue that a limit of 500 N is too restrictive based on the logarithmic fatigue failure model of back injury. Instead, a threshold of 700 N has been suggested as acceptable limit for the majority (90%) of workers for more frequent lifts, up to 1000 repetitions per day (Gallagher and Marras, 2012). A summary of thresholds for low back shear and compression forces in the literature are summarized in Table 14.

Table 14: Summary of Low Back Compression and Shear Force Limits in the Literature

Force	Study	Limits
Low Back Compression	NIOSH (1981)	Action limit = 3433 N
	Waters et al. (1993)	Maximum permissible limit = 6376 N
Low Back Shear	McGill et al. (1998)	Action limit = 500 N
	McGill et al. (1997)	Maximum permissible limit = 1000 N
	Gallagher and Marras (2012)	Action limit = 700 N > 100 lifts/day and < 1000 lifts/day
		Maximum permissible limit = 1000 N < 100 lifts/day

When it comes to joints besides the low back, there are limited thresholds analogous to the NIOSH action or maximum permissible limits. One way to determine thresholds would be to base acceptable joint moments on population strength. These could be estimated or based on averages from a database. Design guidelines generally accommodate the 75% of female strength, 99% of male strength or 90% of the population strength in a manual handling task (Karwowski, 2006). Maximum joint strength for a particular action depends on the posture of the individual which makes it difficult to make estimates of population strength. Chaffin et al. (2006) provide equations that predict population strength as a factor of segment angles and gender for the torso, shoulder, and elbow. There are also population strength databases for different isometric and isokinetic movements at various joints (e.g., Hogrel et al., 2007; The National Isometric Muscle Strength Database Consortium, 1996; Meldrum et al, 2007; Claiborne et al., 2006).

Another option would be to set acceptable levels of forces and loads based on in vivo measurements of contact forces within joints for normal and high impact activities such walking on level ground compared to jogging or jumping. The Orthoload database has reports standardized in vivo forces and moments measured by implants to represent typical loading in the hip and knee joints (www.OrthoLoad.com; Bergmann, 2008). However, these threshold options would not be specific to masonry or representative of masonry tasks and associated loads.

An assessment method with thresholds based on the joint loads of expert masons was proposed to make the biomechanical data more accessible and applicable in industry use. Since expert masons were previously shown to maintain high productivity while minimizing joint loads (Alwasel et al., 2017a), the joint loads of expert masons were assumed to be representative of safer lifting behaviours. This chapter focuses on the development of masonry-specific joint thresholds and proposes a quantitative scoring system to make it user friendly and easy to understand. **Rather than make a direct connection to injury risk, the purpose is to model expert behaviour for comparison to against apprentice technique, with the assumption that long time experts have developed techniques that are implicitly safer.**

4.2 Methods

4.2.1 Data Collection and Processing

Eight expert masons were recruited from the Ontario Masonry Training Centre (Mississauga, Ontario). The participants were all healthy, red-seal journeymen with 20 or more years of experience and no self-reported history of injury. All the experts were male masons, with an average height of 179.63 cm (±4.78) and an average weight of 90.8 kg (±12.03). Their average age (estimated based on years of experience and typical masonry career commencement) was over 40 years old.

Participants completed seven different masonry tasks (Figure 37). The first four tasks consisted of building a standard wall from a pre-built lead wall, building a reinforced wall (rebar), building a wall under a ceiling (in a constrained space), and laying the first course of a standard wall, all using 20 cm hollow concrete masonry units (CMUs), weighing 16.6 kg. The last three tasks consisted of building a wall individually using 30 cm hollow 23 kg CMUs, building a wall while collaboratively lifting with another mason, using 30 cm hollow 23 kg CMUs followed by building a wall while collaboratively lifting with another mason, using 30 cm semi-solid 35.2 kg CMUs. These seven tasks were chosen to represent the variety of physical demands in the masonry trade. Tasks were completed in an established order (order outlined as described) to facilitate experimental set-up for modifying the block configurations. Between each of the tasks, participants had a 15-minute break while the experimental configurations of the wall were rearranged to prepare for the next task. After the first four tasks, participants had a one-hour break. After this break the following 3 activities were completed in order.

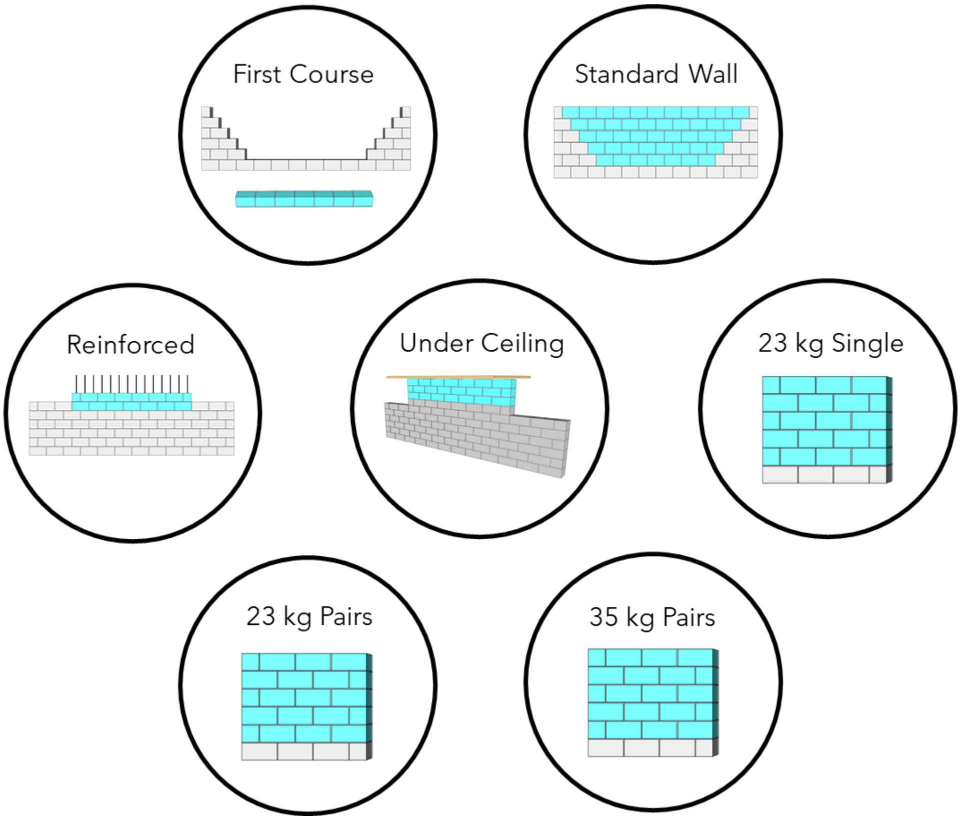


Figure 37: Seven Masonry Tasks Included in Data Collection

All tasks were completed once by each participant; however, each individual block was considered 1 lift. Participants laid 7 CMUs for the first course, 45 CMUs for the standard wall task, 15 CMUS (13 full units and 2 half-units) for the reinforced wall, and 22 CMUS for the (20 full units and 2 half units) for building the wall under the ceiling. However, half-units were excluded from the analysis to focus solely on the handling of standard full-sized CMUs. In the last 3 wall-building tasks with different size CMUs with and without collaborative lifting, participants laid a total of 20 CMUs (15 full units and 5 half-units). Data samples were collected continuously for each of the tasks outlined above. However, the data was segmented based on each CMU lift. Each lift was defined as the moment the participant picked up the CMU to the moment the CMU was placed on the wall – thereby omitting time spent spreading mortar. The segmentation of the data was based visually on the accompanying recorded video of the task.

The total lifting time to complete each task ranged between ~22-36s for the first course, ~117-164s for the standard wall, ~40-100s for the rebar wall, ~ 99-124s for the constrained wall under the ceiling, ~65-100s for the individual build of the 23kg CMU wall, ~46-102s for the collaborative build of the 23kg CMU wall and ~42-65s for the collaborative build of the 36kg CMU wall. This time omitted the lifting time in which one participant had to hold the CMU for longer while their partner spread mortar. The average time per lift for the first course, the standard wall, the rebar wall, and the constrained wall under the ceiling was 3.94s (±1.37), 3.06s (±0.79), 5.94s (±1.73) and 5.56s (±1.67), respectively. The average time per lift of the individual build of the 23kg CMU wall, the collaborative build of the 23kg CMU wall and the collaborative build of the 36kg CMU wall was 5.35s (±1.28), 4.19s (±2.49) and 3.87s (±0.83).

The collection of IMU data used the same techniques as described previously in Chapter 3, section 3.2.2. Similarly, the joint forces and moments used the same model as described in Chapter 3, section 3.2.3. For a full description of both the data collection technique and processing, and a full report of measured joint loads, please see Ryu (2020).

4.2.2 Data Analysis

The motion data collected from the eight masons was used to estimate the peak joint loads representative of expert movement in masonry. The peak joint forces or moments per lift, per participant, was averaged across all tasks to calculate the average loads within masonry at each of the joints. The average peak loads were then used to establish a threshold that models the upper limit of expert joint forces and moments, accounting for a wide variety of masonry tasks and physical demands.

Since all the expert motion data came from male participants, a ratio was used to determine equivalent thresholds for female masons. Lifting strength of females was reported to be between 60-76% of male lifting strength on average (Mital, 1997) with both overall strength and back strength reported as roughly two thirds of their male counterparts (Holloway and Baechle, 1990; Plamondon et al., 2017). The values range differ slightly between lower body strength and upper body strength (Holloway and Baechle, 1990; Miller et al., 1993) but based on overall strength ratios in the literature, the female thresholds were set to 66% of the male force or moment equivalent for all joints. Given the difference in muscle size and strength, it is assumed that females will exhibit the same strength decrements observed in the broader population. Similarly, it is assumed, that these thresholds will also represent a relatively safer magnitude of load like the expert male masons.

4.3 Results and Discussion

Expert masons experienced the greatest peak L4/L5 compression forces when completing the heavy individual wall build with 23 kg CMUs, followed by the first course wall, Figure 38. For two of the seven masonry tasks analysed (28.6%), the L4/L5 compression forces exceeded loading threshold recommended by the National Institute of Occupational Safety and Health (NIOSH), namely the action limit set to 3433 N, by 460.4-482.7 N (13.4-14.1%; NIOSH, 1981). However, the overall average of peak L4/L5 compression forces sits around that acceptable action limit range. All A/P shear forces were below the recommended shear action limit for lifts over 100 lifts/day by 5.6-408.3 N (0.8-58.3%; Gallagher & Marras, 2012).

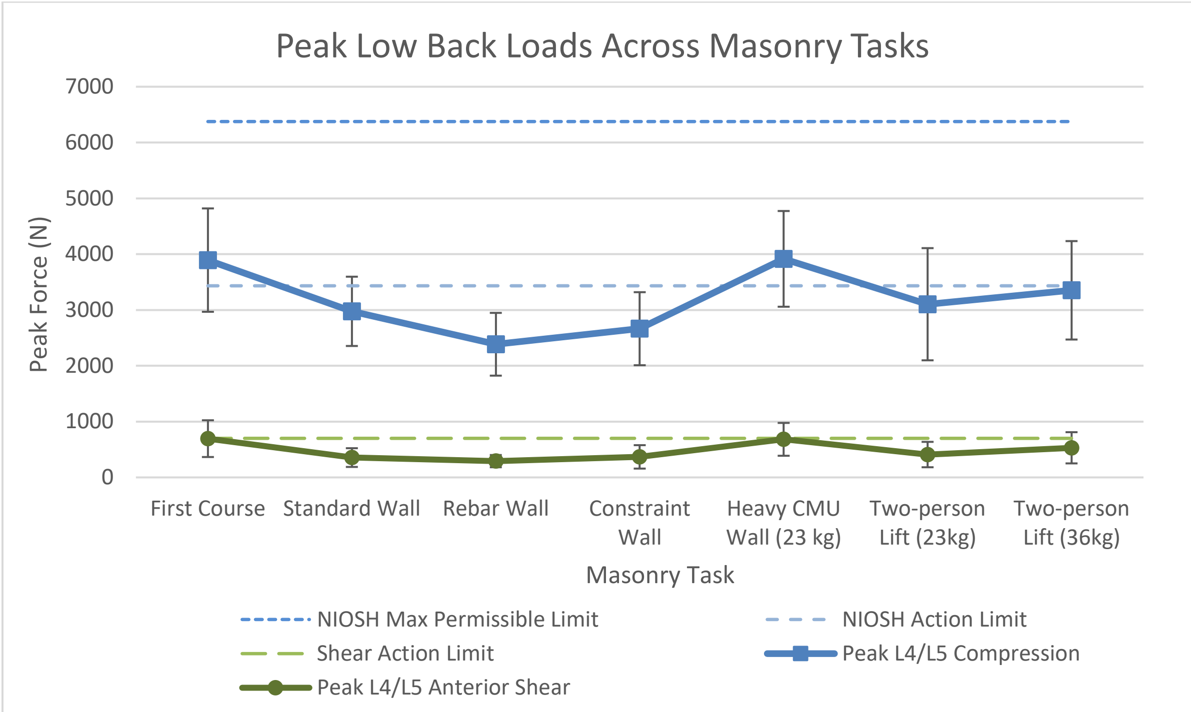


Figure 38: Peak Low Back Forces Across Masonry Tasks

It should be noted that these values represent peak forces rather than average forces. Peak forces and moments were used as thresholds to account for the individual variability and the range of values around the mean to better establish an upper limit for risk. There are a limited number of options for moment thresholds recommended to prevent injury for these body joints in the literature, which is why it was necessary to develop our own from this data. Tools like the duty cycle equation (Potvin, 2012) or LiFFT (Lifting Fatigue Failure Tool; Gallagher et al., 2017) can be used to estimate acceptable joint moments or cumulative damage. However, given that the time of exposure while lifting a load is typically 1-2 seconds, the predicted maximum acceptable effort decreases rapidly due to the low duty cycle. For this reason, duration and associated impacts of fatigue are outside the scope of this thesis. Nevertheless, this statement does not apply to other masonry tasks such as lifting rebar where the shoulder is loaded for a longer period. It should also be noted that in masonry, the number of repetitions and the weight of the block are not easily alterable due to constraints within the trade. Since these are measured forces from expert journeymen with no history of injury, we can assume they represent a reasonably safer upper limit for the profession.

The peak expert forces were used for the threshold and scoring system due to their specific applicability to the masonry industry. This aligns with our overall goal of modeling expert mason behaviour. Nevertheless, the established thresholds for peak low back compression and shear forces falls below the NIOSH action limit and the recommended shear limit. Therefore, the low back compression threshold aligns with the recommendations of the literature, and maybe more conservative in nature (note: the established threshold values are not direct related to epidemiological data or injury risk).

Experts experienced higher peak moments on the lower body compared to the upper body, (Figures 39 and 40). For the lower body, the highest moments were experienced during the build of the first course wall and the heavy individual wall builds with the 23 kg CMU (Figure 39). For the upper body, the rebar wall, the constraint wall and the heavy individual wall build with the 23 kg CMU resulted in the highest moments (Figure 40). The lower body joints all experienced peak moments within a range of 100.6-198.1 N•m with the left ankle joint and the right hip consistently experiencing the highest moments throughout the seven tasks. For the upper body, the joint moments all fell within a range of 2.5-42.0 Nm, with the left and right shoulders consistently experiencing the highest moments. This falls in line with previous research that indicated the shoulders are the second leading body part affected by MSDs in construction (CPWR, 2019).

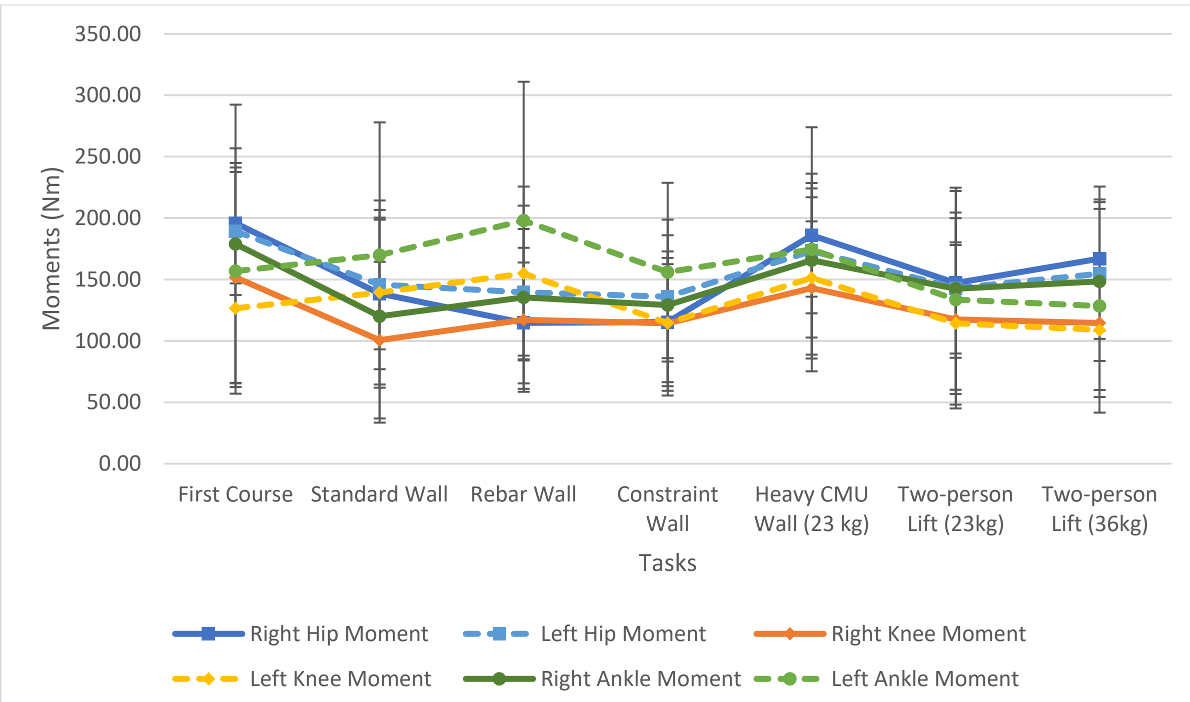


Figure 39: Peak Lower Body Joint Moments Across Masonry Tasks in Experts

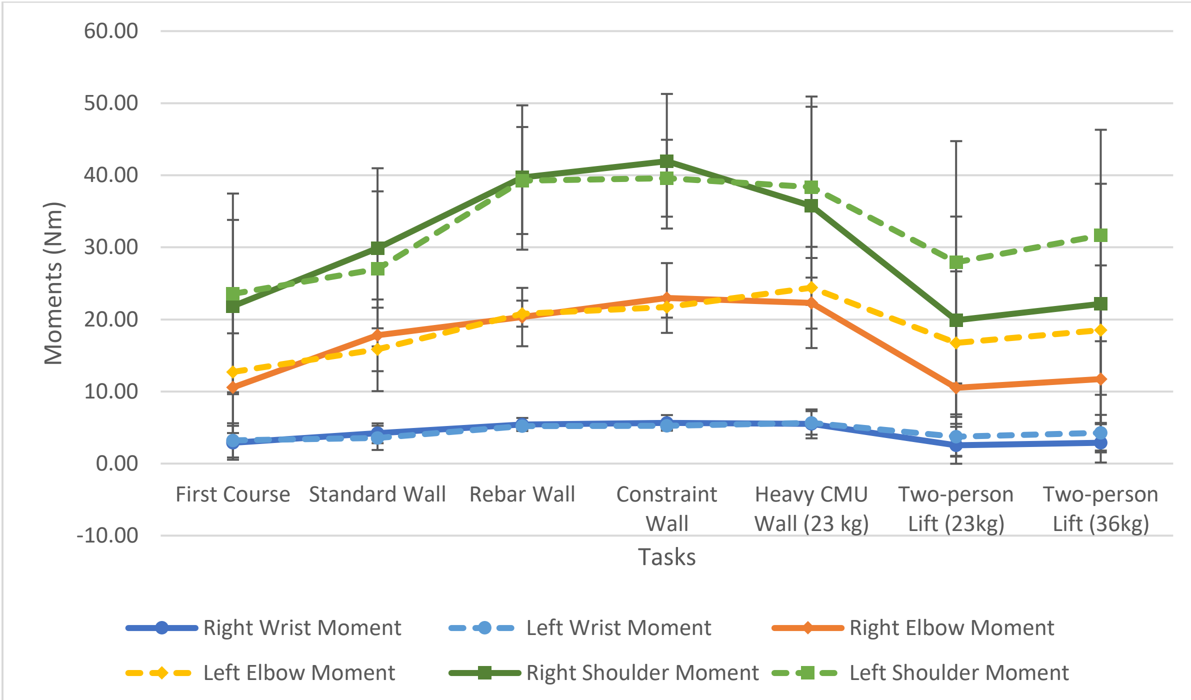


Figure 40: Peak Upper Body Joint Moments Across Masonry Tasks in Experts

For implementation within the enhanced assessment tool, the peak forces were averaged across all seven masonry tasks. Additionally, equivalent female forces and moments were calculated for each of the joint thresholds to provide sex-specific thresholds (Figure 41). The basis of this model is rooted in theories of injury causation in which high cumulative loads or overexertion will increase injury risk (Kumar, 2001). The focus of this thesis is primarily on instances of high force exposure as modeled in expert lifting behaviour rather than cumulative loading or fatigue. Therefore, the goal is to reduce or eliminate occurrences of excessively high loads, with the assumption that this may lead to safer lifting. All of the joint moments have an associated threshold for the sake of completeness. The following assumptions are made with respect to the thresholds described in Figure 41:

- Thresholds are not directly related to risk levels. They are based on expert lifting behaviour, which is assumed to represent a safer lifting technique.
- Magnitude of the joint moment load is assumed to be a critical element within the causal pathway of injury.
- Peak joint exposures are the major concern, independent of the number of cycles of exposure (i.e., thresholds do not consider a frequency, duration or duty cycle element).

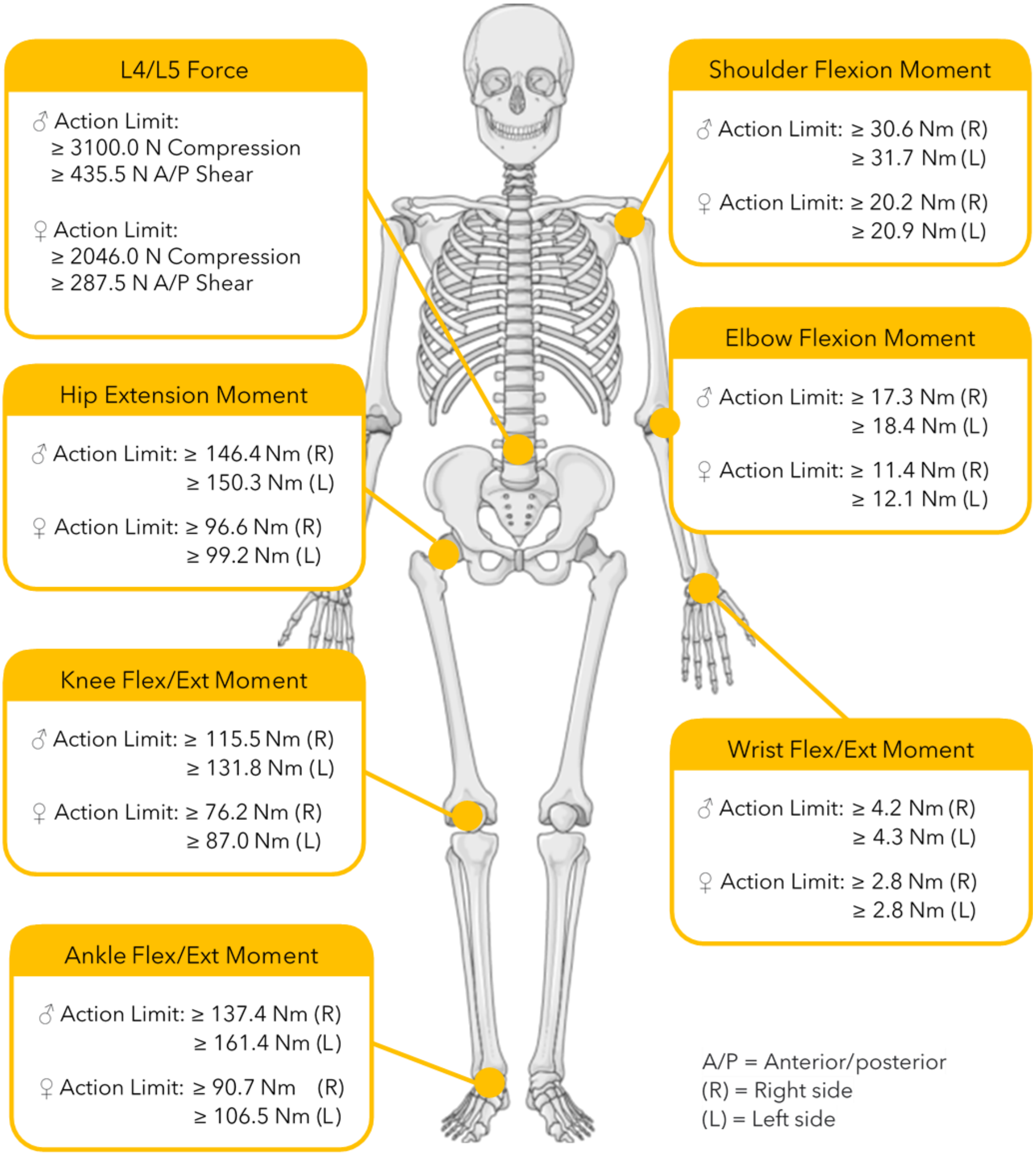


Figure 41: Male and Female Joint Load Thresholds Implemented in the Training Tool

4.4 Scoring System

The thresholds were established to provide a means by which to assess joint forces and moments measured onsite and compared to expert masons. These forces and moments will be measured using the IMU suits and inputted into the enhanced training tool to identify instances of high loads during masonry tasks. To link the measured forces and moments to injury risk, a scoring system was established, making use of the aforementioned thresholds. The scoring system consists of an equation to calculate individual joint scores, and an equation to calculate the whole-body score.

The joint score (S_J) is calculated as the ratio of the joint load (moment in N•m or force in N) to the respective action limit (moment in N•m or force in N; Equation 1):

$$S_J = [Joint\ Load/Action\ Limit] \times 100 \quad (1)$$

The whole-body score (S_{WB}) is the weighted sum of the joint scores (S_J) for all the joints in the body (Equation 2):

$$S_{WB} = [\textstyle\sum_A (Joint\ Load/Action\ Limit) \times 1 + \sum_B (Joint\ Load/Action\ Limit) \times 0.5] \times [100/9] \quad (2)$$

Where:

- Peak expert load thresholds were established as the action limits
- Joint group A (L4/L5 compression and shear forces, as well as the left and right shoulder flexion moments) are fully weighted to reflect greater contribution to the joint score
- Joint group B (all other joints, namely left and right elbow, wrist, hip, knee, and ankle, flexion/extension moments) are half weighted.

The whole-body score is weighted to prioritize exposure at the low back and the shoulders based on past evidence of increased risk for these joints in construction (CPWR, 2019). The sum is then multiplied by a factor to produce a final numeric score. While the focus of the scoring system is on the low back and shoulders (higher weights within the equation), other joints along the kinetic chain (lower weights within the equation) were included in the equation to provide a complete picture while communicating with apprentices. The scores are then contextualized for risk as depicted in Figure 42. The ratings shown in Figure 42 applies to both whole-body and individual joint scores because the system uses relative weighting compared to the thresholds established by the expert masons. This figure does simplify several concepts with the intent of communicating directly to trainees.

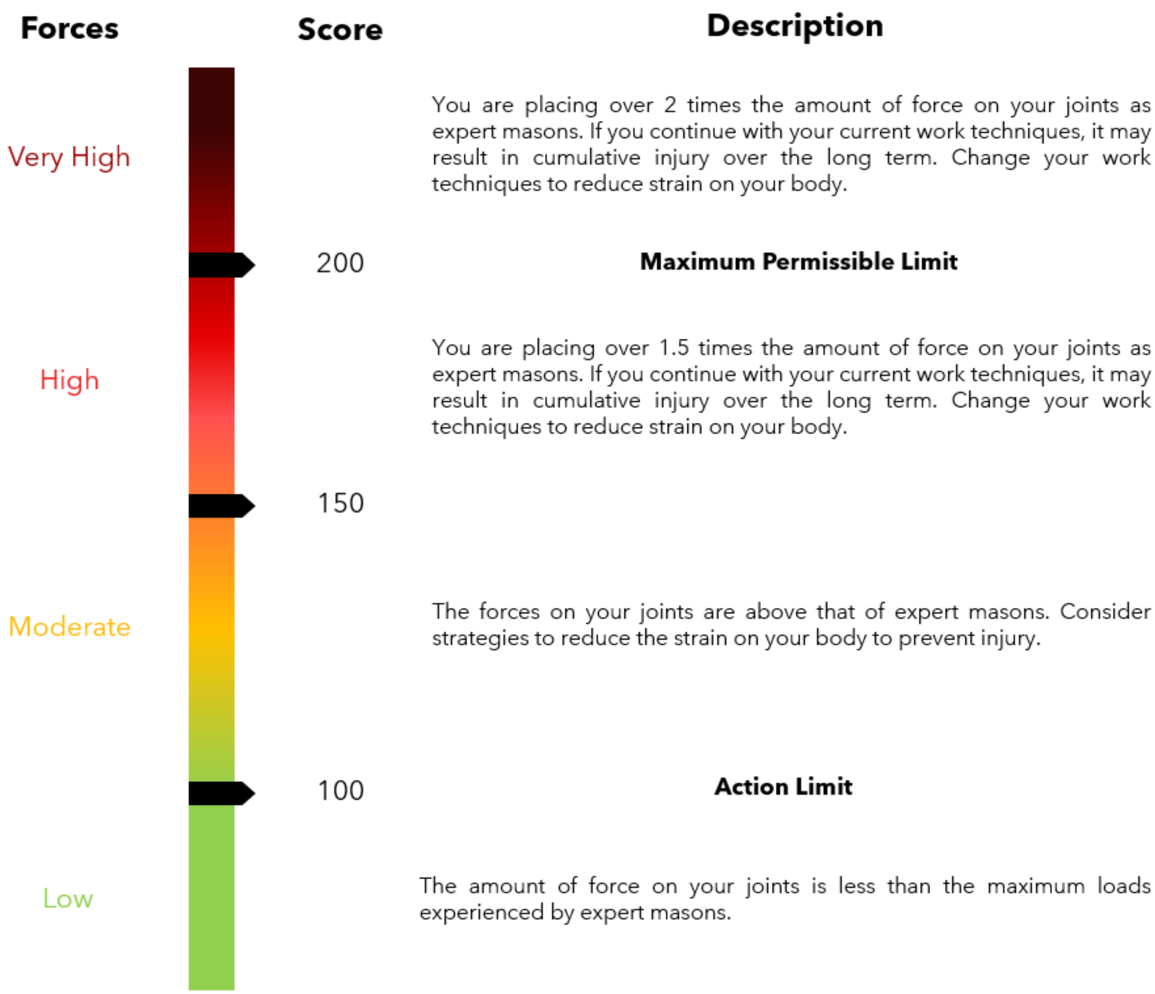


Figure 42: Scoring System

These thresholds and scoring system will be implemented into the enhanced training tool as the new criteria for critical point identification. This is used in the training tool to score each joint load of the apprentices against that of expert masons to compare their behaviour and benchmark their outcomes. The critical points will be based on individual joints scores (S_J) larger than 100; joint loads that exceed their respective action limit. Alongside individual joint scores, the whole-body score (S_{WB}) will also be provided. The scoring chart shown in Figure 42 provides additional context and make these scores more meaningful to apprentices. The scoring system is useful such that it provides feedback on an outcome measure correlated with changes in their technique over time, allowing them to track their progress during training. This scoring system has no direct implication upon injury or MSD risk, due to a lack of epidemiological data. Rather the intent is to model expert behaviour which has been shown to correlate with reduced exposures and potentially safer behaviour while lifting.

Chapter 5
User Interviews: Qualitative Data Collection and Analysis

User interviews were conducted with masonry instructors to gain insights about themselves and the apprentice classes prior to developing the training system. As experts in the field and a wealth of knowledge on apprentices and the trade itself, we were able to gain insights into the safety culture within masonry and assess the current level of knowledge and approach regarding training on MSD risks. Instructors were also able to give feedback regarding the design plans and concepts for the enhanced training tool as well as feedback regarding the structure and resources for an accompanying in-class educational module to supplement the hands-on training tool. This input was valuable and necessary to gain a deeper understanding of the context for the training system and its end-users, prior to the final design and development.

5.1 Background

To become a certified mason in Ontario, there are 3 levels of apprenticeship with a minimum number of job hours between each level. At each level of apprenticeship, apprentices must take an 8-week skills training course. After finishing the level 3 apprenticeship training class, and the required amount of on-the-job training hours, apprentices can apply for the Journeypersons Class at the Ontario College of Trades and challenge the interprovincial 'Red Seal' certificate of qualification examination. After passing, they will meet the provincial qualifications to be recognized as a red seal endorsed journeyman.

The following terminology will be used throughout this chapter:

- **Apprentice skills training course:** 8-week course focused on vocational skills for levels 1, 2 and 3.
- **Training Program:** a training program for ergonomics, focusing on lifting technique and MSD risk information that spans 3 levels of apprentice skill training courses.
- **Training Tool:** the software and hardware associated with the enhanced training tool for manual handling, for the in-shop component of the training program.
- **Educational module:** the in-class component of the ergonomics module within each of 8-week courses.

5.2 Methods and Analysis

Qualitative interviews were conducted with 8 instructors from the OMTC. The eight instructors had an average of 23.9 years of experience as a mason with a range between 10-43 years total. As an instructor, they had an average of 6.9 years' experience with a range between 1.5-18 years.

CMDC reached out to OMTC on our behalf to recruit participants for the interviews. Prior to the interviews, a meeting was scheduled with stakeholders from CMDC to refine the interview questions for the target audience. The first interview was conducted with the director of training for the OMTC, and previous instructor (able to reprise role as an instructor at any time). This interview was conducted with stakeholders from CMDC present to act as liaisons and to provide additional context for either party as needed. The last 7 interviews were conducted without CMDC present. The interviews followed a semi-structured format and were audio recorded with the consent of the interviewees. Post interviews, the audio recordings were transcribed.

Thematic analysis was conducted using a template methodology (King et al., 2018). A few a priori themes were identified based on the research questions (Figure 43). For the first section of the interview about safety in masonry, these a priori themes were physical demands and MSD risks, experiences with injuries, and injury prevention behaviours. For the second section of the interviews, regarding user feedback about the training tool and program, the themes were concerns, desires and suggestions, resources, program time allocation and scoring metrics.

Preliminary coding was completed for all the interview transcripts, during which relevant information was identified and annotated. Then a priori themes and emerging themes were clustered together, and an initial template was created (Figure 43). The template was then applied to all the data and altered as necessary to best fit the data. After further changes and development, a final template was established encompassing the themes in the data. The final template is represented in the thematic analysis maps (Figures 44 & 48) represented in the results sections 5.3 and 5.7.

A Priori themes:

Safety in Masonry

- Physical demands/MSD risks
- Experiences with Injuries
- Injury Prevention/behaviours

Training Tool & Program Feedback

- Concerns
- Desires/suggestions
- Resources
- Program Time Allocation
- Scoring metrics

Initial Template:

Safety in Masonry

- Physical demands/MSD Risks
  - Age
- Experiences with Injury
  - Injury experiences
  - Seeking medical help
- Safety Culture/Attitudes
  - Age
  - Instructors
  - Industry
- Learning Experiences
  - Experience
  - Knowledge Sharing
  - Instructional Courses
- Role of safety in courses
  - As apprentice
  - Current curriculum
  - Informal teaching
  - Advice
- Risk Modifiers
  - Anthropometrics
  - Age
  - Causes of injury
  - Fitness/conditioning
- Safety behaviours
  - Stretching/warm-up
  - Technique
  - Equipment
  - Other

Training Tool & Program Feedback

- Concerns
- Resources
- Suggestions/Desires
- Program Time Allocation
- Program Structure
- General Feedback
- Scoring

Figure 43: A Priori Themes and Initial Template for Thematic Analysis

5.3 Results: Ergonomic Knowledge and Attitudes in Masonry

The thematic analysis map (Figure 44) outlines the themes and subthemes identified in the interviews regarding ergonomic knowledge and attitudes in masonry. These themes will be discussed in further depth in the following results section.

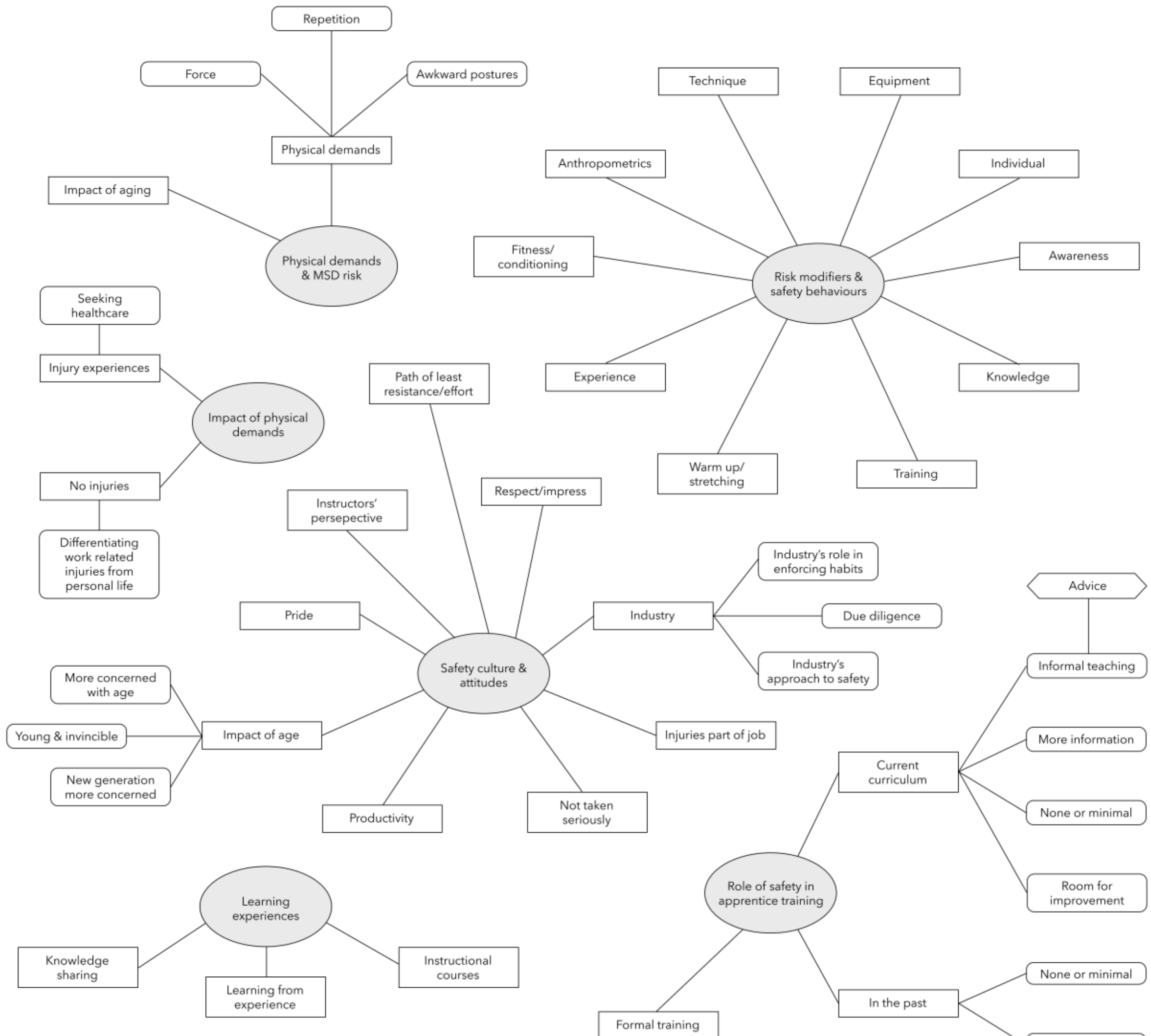


Figure 44: Thematic Analysis Map of Safety in Masonry

5.3.1 Knowledge of Muscle Injury Risks and Prevention

The instructors were asked to rate their own knowledge and the knowledge of the students on muscle injury risks and prevention strategies on a scale from 0 to 10 (Figure 45 and Figure 46).

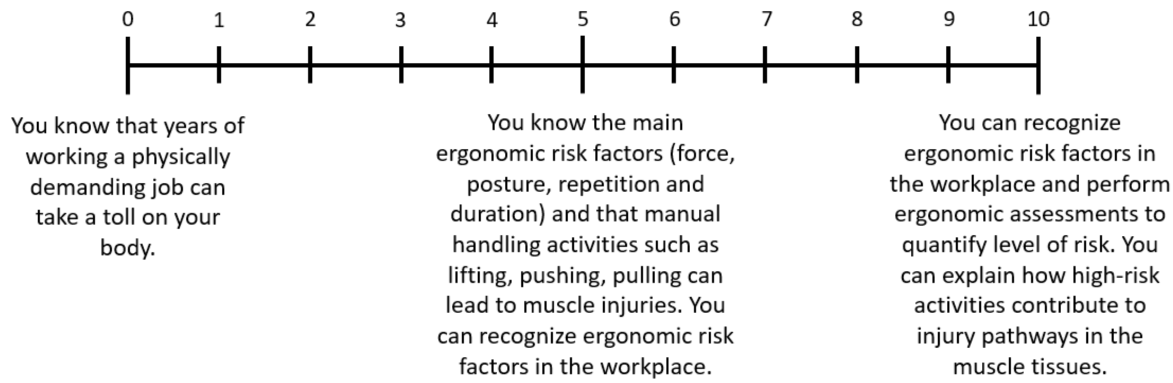


Figure 45: Scale Used to Rate Knowledge of Muscle Injury Risks in Masonry

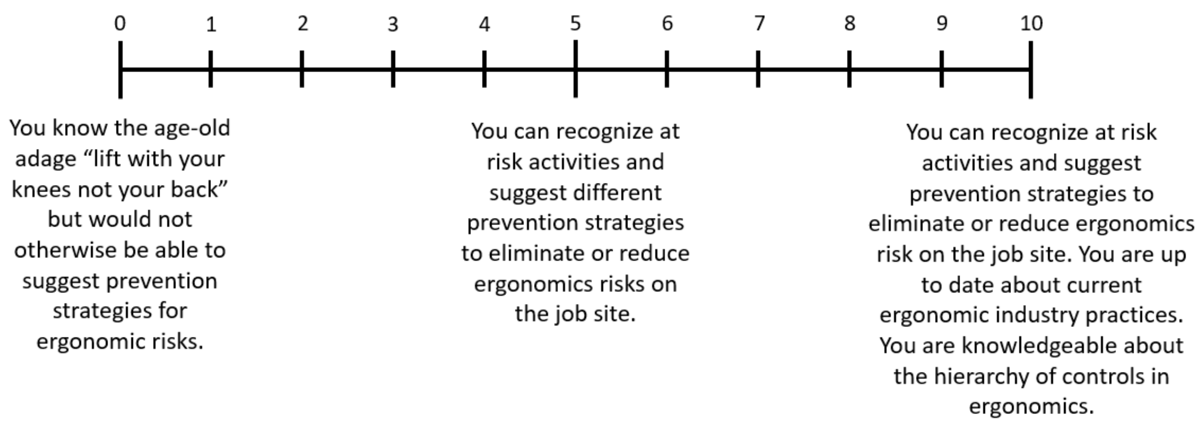


Figure 46: Scale Used to Rate Knowledge of Prevention Strategies to Reduce Muscle Injuries

On average, the instructors rated themselves similarly for both muscle injury risks and prevention, but for the apprentice groups, they rated their knowledge of prevention strategies slightly lower (Figure 47). The instructors had the most knowledge of the experience groups with an average rating of 7.3-7.4 whereas the 1st year apprentices had the least (1.6-2.4). The apprentices' knowledge increased as they gained years of experience. The greatest increase in knowledge occurred between the 1st year and the 2nd year with an increase between 106.1% to 169.6%. The increase between the 2nd year and the 3rd year was smaller with an increase of only 22.1% to 24.1%. While the 3rd year apprentices had the highest knowledge rating of the apprentice groups, they still had less knowledge than the instructors by about 20.3-24.1%.

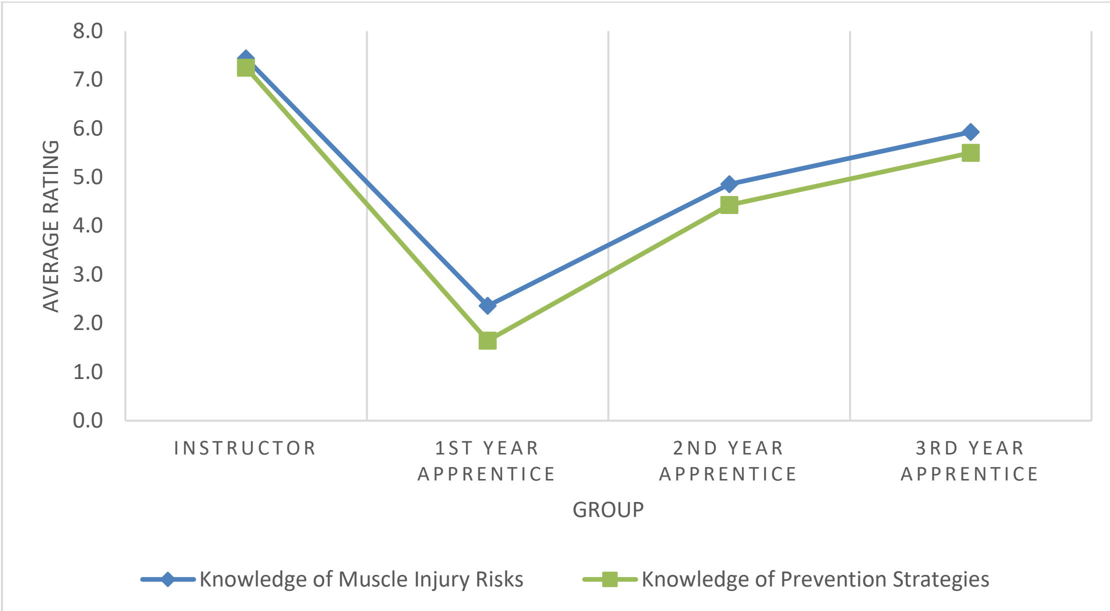


Figure 47: Knowledge of Muscle Injury Risks and Prevention Strategies of Instructors and Apprentices in Masonry

5.3.2 Safety in Masonry

On the topic of ergonomics within masonry, the instructors highlighted their own experience in the trade in terms of physical demands, injuries, safety culture, learning experiences, the role of safety, and risk modifiers. These themes gave insight into the overall culture, attitudes, behaviours, and experiences of apprentices and masons regarding muscle injury risks and prevention.

5.3.3 Physical Demands and MSD Risk

Strenuous physical demands were a major theme within the instructors' relationships to their jobs and to the topic of musculoskeletal risk and prevention. The instructors highlighted the demands placed on their body every day, and the impact of aging on their ability to withstand those demands. High forces, repetition, awkward postures, and lack of rest were highlighted in the instructors' accounts as major demands within the trade:

> *Like it's there's a lot of lifting, bending, crouching, working on your knees… you know it's very hard on the joints that's just all there is to it, right.*

> *Its just a lot of repetitiveness, understandably enough we're having our trowel in our hand other than lunch and break… it's 40 to 50 hours a week, right. So. Your hand is always clenched tight, so, and then of course there's like laying --laying blocks is really more the demand of it. Bricks is one thing, its nice and light, it's in your hand, but when you're lifting a 50-60 pound block over and over and over and over and over again. It definitely beats up your body quite quickly, right.*

If you lay block for an entire day, you likely move a few 1000 pounds of mortar over your trowel. So just with one forearm, you're moving hundreds or thousands of pounds.

Many of the demands were emphasized as part of the job. That the physical demands were the reality of the trade, and that while prevention is important, elimination is not feasible or realistic:

These materials that you're lifting are never gonna change. The dimensions are always going to be the same and the weight will always be there.

Instructors emphasized the toll that these demands can place on masons' bodies over the long term:

I'm a firm believer no matter how fit you are, if you're doing masonry all your life, you're punishing your body plain and simple. So, about the time you're 60-65 years old, if you haven't figured out something else to make a living… Like if you been a journeyman, let's say, which some guys are, that's fine, they want to lay brick and block all their life, get their check and go home… there's gonna be permanent damage there… there's 100%, just no two ways.

Several of the masons touched on how aging reduces their physical capabilities to keep up with the physical demands of the job:

This trade is no joke, I mean, it's-- and especially if you want to stay in it for 10, 20, 30 years. It's you know it's a humbling trade, I'll tell you. It doesn't get any easier, it only gets harder because your body of course requires more of itself as the years go on, and you've got less of it, right, less muscle, less patience, less everything. […] Five years ago I was not even thinking of teaching, I was just laying block, doing my thing and hey I could do this forever, right, and then all of a sudden, just something changes in you, something changes in your body, and it's very scary, right.

Even one of the youngest instructors at OMTC, noticed the effects of aging on his body with respect to the job:

As I age, I do notice every action is just mildly more difficult.

5.3.4 Impact of Physical Demands

Most of the masons mentioned that the physical demands had taken a toll on them and resulted in some minor wear or tear; however, only a few mentioned having some experience with injuries. Of those that had injuries, the severity of their experiences varied. Several mentioned their personal experiences with being injured due to the job demands:

So that that little window of my life led to a wrist injury, but I quickly, you know, I saw some help but I got some advice and guidance and then I kind

> *of changed my view and adjusted my approach in sort of-- so I dealt with that injury at that time. So, it wasn't like years and years of problems, it was like maybe six months to a year, where I kind of got through my stubbornness and I figured it out.*
>
> *I mean I've had back issues off and on throughout my career.*
>
> *I felt something weird one day like this is like my first or second year as an apprentice and I was moving a wheelbarrow and I stepped on something and I had a little pain in the lower back and I wasn't sure what it was, anyways, I left it alone and it didn't really bother me and then I'd say 4-5 years later I was lifting some bricks out of the back of the truck and I was in a weird position , I forgot to do the usual warm-up routine and I felt like I pulled something*
>
> *Shoulders for sure. My right arm for sure. It goes without saying… three maybe four days in a week, my arm in the middle of the night is completely numb.*

For those who had experienced an injury, it was usually severe enough to seek medical treatment. Instructors sought the help of a variety of healthcare professionals including chiropractors, osteopaths, physiotherapists, and doctors. After receiving proper treatment, masons were able to recover and go back to their job:

> *But like I said low and behold I ended up going to physiotherapy and the lady there had this --basically described to me that the scar tissue over the tear I had was basically fusing my shoulder in an incorrect way based on the injury I had. So she literally bent this thing backwards and forwards and she goes I'm sorry I know you like --you don't want to show up here anymore 'cause you're in pain but she goes I have to do this. I have to bring your shoulder back to the way it was. And honest to God I can't thank her enough because my shoulder feels 100% brand new again.*

Only some mentioned persisting injuries post treatment. On the other hand, several masons have mentioned that they have never had a major injury over the course of their career:

> *I've never been hurt. I've never been off work… yeah feeling pretty strong still. Yeah, I just don't know, as I'm getting up in age it's maybe the lower back's starting to feel it, but… knees, in my elbows but… nothing that's hindering me from doing my job.*

To deal with some of these physical demands, some instructors mentioned substance use. One instructor mentioned relying on drugs from their doctor to deal with the muscle pain while another brought up the problem of substance abuse in the construction trades:

> *It's in construction, you know, any real trade, but go any trade to the next and there's a lot of substance abuse, well often because people are going to*

> *work sore and then you know, the first one's free and the trades are hurting, and they're physically… not just bricklaying.*

When reflecting on how the physical demands of the job have impacted them, several masons also mentioned that it was hard to distinguish which impacts on their body were work related and which were related to recreational sports activity outside of work or aging:

> *I mean I don't know where you cut the line between aging and what your work is doing to you, right. It's hard in my personal life too I also… I've been playing soccer since I've --I was four and so those physical activities are definitely not helping either. So, it's really hard to know what part of, you know, my physical being has to do with work and where it has to do with soccer and everything in the middle. Because I'm also an active individual, right.*

5.3.5 Safety Culture and Attitudes

Safety culture and attitudes towards safety was another theme in the data. All the attitudes described were interpreted through the perspective of the instructors themselves, including their own experiences and attitudes as well as their perceptions of the apprentices' attitudes and the industry's attitudes towards safety and ergonomics.

One of the most common aspects brought up by the instructors was the impact of age on safety (75%). Most of the instructors said that younger apprentices were not as concerned about the impact of the physical demands on their bodies. Young apprentices often tend to believe they are invincible and approach tasks with this attitude:

> *Everyone is young and that so, you know, you're gonna beat your body up because you're invincible.*

> *When I was young and 21…22 and getting into masonry the last thing I was thinking about is how to stretch and I mean you're –you're fit, like Superman, right. So, end of the day you're not really too overly cautious about it.*

On the other hand, the older masons are more concerned about the impact on their body, and take the steps to prevent injuries:

> *It's actually kinda funny 'cause we were talking and guys were just giving stories back and forth, and they were saying you know on this commercial site where you get into an elevator, the young guys are getting in the elevator and going all the way up and you see the older boys are walking the stairs all the way up and of course young guys like why would you want to take the stairs and they're like this is how we warm up our muscles, right?*

It is only as the younger apprentices age, and by extension gain more experience, that they become more concerned about the muscular strain of the trade (62.5%):

> *Yeah, for sure, 100%, that changes. Because either a) they get injured or b) they see someone that gets injured or 3) or c) they get to a point their life where they start to realize that they're not gonna be young and healthy forever so now their focus switches to health which coincides with their work environment.*

Conversely, some of the other instructors said that the incoming apprentices in the current generation are often more concerned about the physical demands of the trade (25%), compared to apprentices in the past:

> *Yes. More and more of them [are concerned about the physical demands] if I'm being honest. It was not that way when I came in a decade ago. Again, it was still kind of a-- I don't want to say rougher environment, but in general I feel that trades are changing really fast for the better, which is a great thing. […] I'm gonna say the vast majority of them are concerned. When I do info seminars where we talk to students at high schools, where people interested in our pre apprenticeship programs or entry level programs, it's one of the most common questions.*

In the masonry trade, income is based upon work performance, which creates a pressure to maximize productivity (50%). This emphasis on productivity can come at the cost of their own physical condition by taking on too much, cutting corners or not taking the time to think things through:

> *So much is judged on your output and for myself my income is judged on my output so I do pull sometimes more on myself that probably should and until I get to that point where I feel sore, I probably go past where I should physically. And I do not monitor it until it flares up, which isn't something I'm proud of and it's something I should work on but it's --that is the truth.*

Around half of the instructors mentioned that apprentices often have an indifferent attitude towards safety, and that they find it hard to get through to the apprentices:

> *On a pack of cigarettes, they have these terrible looking things about, you know, bad lungs and this and that. All these pictures but as soon as they get used to the pictures, it doesn't mean anything to them, they just buy the cigarettes anyways and the safety is the same thing. […] I think until you can convince somebody between their ears that safety is some value to them, I think, until you can convince them between their ears, that safety is of value to them… I think you could teach it as much as you want, all day long whatever, I don't think it'll make much of an impact and I've seen this so many times, firsthand.*

There is also an overall attitude within the trade that injuries are just part of the job, which was expressed by several instructors:

> *It's part of the job, you're gonna get hurt. The lifting's always the same, you always got to lift.*

Not only did instructors reflect on their own and other masons' attitudes, but they also highlighted the impact of the industry on the overall culture and its contribution to safety attitudes within the trade. While the interview with instructors focused on the ergonomics within the apprentices' skill training classes, they emphasized that the industry plays a role in not only training proper habits but also setting expectations for workers. While ingraining good habits is critical in trade school, it's only a part of the big picture:

> *A lot of that too is we only get them in trade school for a little bit then the industry has to do the rest of the work. Whether they're learning it from us or they're learning good or bad habits from the industry. If you learn something one way, but then, you know, when you get into the industry and it's… the stresses and demands, you know, you might… that's where you kind of that's where you let your hair down and make those mistakes. I know contractors want to make money, but do they want to lose time on injuries. I'm not asking about steps… maybe 100 less blocks a day or something, you know, but the industry plays a role in this too and what they set as expectations for people.*

Nevertheless, several of the instructors commended the change in approach to safety within the last decade. Overall safety is being taken more seriously within the industry and the culture towards injuries is starting to shift to the point where getting injured on the job isn't just accepted:

> *Nobody used to talk about it. It was one of those things, that years ago in construction, you just had to --your knees or your back will go, that's how it is and then you have to find something new to do. It wasn't looked at as a long-term career by most people, so nobody --and that was the trade-off, you make a decent wage, but your body may breakdown eventually, just like many other things. And that's no longer acceptable, which is good, it shouldn't be, but I get because of that --the shift is changing and the next generation cares a lot more about that.*

This stance is a bit at odds with other attitudes in the industry where getting injured is viewed as part of the job. However, perhaps this is reflective that the overall culture is still shifting and has farther yet to go. In line with a cultural shift towards safety, the technology implemented on job sites reflects this greater standard for preventing injury:

> *In my 43 years, I'll tell you, there's a lot more equipment that lifts things, whether it be you, or you and your materials, elevating platforms, like climbers on the side of the… like elevating scaffold basically, keeping you at the perfect working height all the time. That's gone a long, long way, you know, machines that can telescope and put materials higher on things and it just eliminates all the back-breaking work. Really, I can attribute, I can see it too, the fact that there's more women getting into the masonry trade and*

> *that's because there is left less lifting involved to certain extent. […] I've worked on parliament hill for six months and it doesn't matter how old you are, whether you're 7 years old or 77 years old, you can lift stones…you know… half as big as your car because there's chainfalls on site. It's stuff like this… they've eliminated so many of those hazards of lifting… and devices to lift things into place, pipes to slide them on. Yeah, the workplace has definitely gotten better.*

On the other hand, one instructor had a more jaded perception of the industry's role in safety and safety training. He personally felt that large companies in the industry treated safety and ergonomics training as just fulfilling their due diligence:

> *I've talked to too many people, very high up the ladder on safety, and a lot of large companies, I mean, they just build it into the price, you know, it's 10% of a job and we'll make sure we deliver all these courses and do all these things so it looks like we're doing our due diligence. But we already know that they're not likely… that the safety… the incidences are going to stay the same rate. That's not their concern… their concern is that we've delivered the course, we've done our due diligence and you know, if something happens, they can't be blamed on us. It's kind of a sad statement but that's what I see it's been reduced to.*

Instructors mentioned that apprentices have a lot of respect for the individuals who have trained them and want to get that respect in return or want to impress them. Sometimes this culture of trying to gain respect or trying to impress can result in apprentices pushing past their limits:

> *I think that also they want to earn their badges in regard to getting respect from the elders and in order to do that, they have to work a little bit harder than the average joe. And sometimes when people push their bodies and their minds to the limits, they make mistakes as well.*

Similarly, masons take a lot of pride in their work and in their abilities and this culture can also lead to masons pushing past their limits:

> *Much of my pain is self inflicted. It's I don't know if it's a pride thing or what --it's definitely a pride thing. I like to work hard. I like to try and put out the most I can. And not super proud of it but I guess I'm not ashamed of it, like many masons I like to attempt to put in more than the masons around me.*

Instructors also mention that masons will take the path of least resistance or effort just to get the job done, whether that be lifting in the way that they're used to, or is the fastest, or skipping out on getting help:

> *It's the last stone that's got to go in, I should get some help… I think I can do it, that type of thing and then, have a little bit of regret later on or whatever.*

Despite various attitudes within the industry that could contribute to injury risk, all instructors thought that safety and ergonomics was important. Many instructors emphasized safety within their classes through informal means such as advice or the types of messaging they share to their students. Typically, instructors share their own unique perspective on the importance of ergonomics and safety framed through the lens of their own experiences:

> *I do mention it, because it-- probably because again I am-- I am already our youngest instructor to my knowledge, there's a few others around my age but it has impacted myself and then other people that I know... so I do try and mention it when I teach just so they're aware of it. […] I try --my exact line to them in the course is that if you go through your career and you put your time in, so you can retire and then by the time you get there you can't walk because you destroyed yourself, what was the point? Because that's how I look at it. I use the same speech for safety gear, like safety glasses and earmuffs and things like this.*

5.3.6 Learning Experiences

A critical difference between the expert masons and the apprentice masons is their implicit and explicit knowledge. As such, identifying how expert masons learn and gain their skills is essential. A central goal to our research is using these findings to transfer knowledge more effectively from expert to apprentice masons to make the training process more efficient.

One of the main ways that the instructors learned about muscle injury risks and prevention, was through the sharing of knowledge (75%) between other masons:

> *Which again goes to stuff you learn from other masons, teaching you stuff and it's just something's quicker and faster and easier on your body […] Even just the way a bricklayer taught me how to spread my mortar with just the turning of the hand as opposed to moving your entire shoulder and body around thing.*

Another common way masons learn about muscle injury risks and prevention strategies is through experience (62.5%):

> *The blocks don't ever get lighter, so yes, the blocks are the blocks and that's all they're gonna be. And scaffolds are going to be scaffold and heights are gonna be heights, and so none of those components will ever change, right. It's only as you get into the trade, year after year, you'll learn the tricks of the trade… you'll learn how to do things much more efficiently and try and save your body while doing it, right.*

> *I've done a lot of restoration work as well… taking large stones out of walls and I think I've become more adept at seeing the hazards and how-to kind of nip them in the butt there before they happen. [Referring to how he learned to see the hazards] Oh 90% is experience for sure.*

> *Because by that point if you haven't identified the motions that can wound you or that, you likely just haven't been on a job site very much.*

Many of the masons thought that apprentices were at greater risk for injuries, for multiple reasons, one of which was lack of experience. Several commented that if the apprentices didn't learn quickly, they'd hurt themselves:

> *Again, if they're still making the same mistakes and possibly by third year, they've hurt themselves with this, so they have an understanding.*

> *You should pick it up fairly quickly like if you don't figure out how to pick up the block very quickly you won't be without hurting yourself. You won't be in the trade very long.*

Only one instructor mentioned learning from a course, when external consultants were brought into the classroom to teach the apprentices about lifting techniques. While he was an instructor at the time, he also learned from the demonstrations that were given to the students.

5.3.7 Role of Safety in Apprentice Training

Another theme was the role of safety, particularly muscle injury risk and prevention, in apprentice training throughout the instructors' careers: in the past, as apprentices themselves, and in the current curriculum as instructors. Referring to their own experiences as apprentices, many instructors (62.5%) mentioned that there was little or minimal focus on ergonomics during their skills training courses:

> *Yeah, there was very little information when I was an apprentice, there was very little information about that sort of thing, you know. I'd say almost zero.*

> *I mean when in school we were told so you know obviously stretch before you start working and you know stuff along those lines, but certainly to go into depths… not much to be honest with you.*

Only a few instructors (37.5%) said that there was a moderate amount of information or focus given to muscle injury risks and prevention when they were an apprentice:

> *It was one that was warming up, right, it was warming up the body in the morning, so we discussed that, and the second part was learning how to lift heavy objects without pulling muscles… so proper stance, which way to move your body while carrying weight…um what else, yeah in regards to actually doing the job there was… ways of moving your body with heavy material without creating injury, the way you walk, the way you position yourself and lift something up on material plank, etc. etc. so we did discuss that, yeah.*

The director of training mentioned that in the current curriculum, the students have more access to information about ergonomics, and that overall safety has a greater emphasis:

> *Well, it's mostly through any of our health and safety courses that we do, that would be the majority of where they're getting the type of information that I didn't get when I was an apprentice. So not all of it would apply to…*

specifically what you're talking about, but in general terms, safety is stressed a lot more and on the job site it's monitored a lot more, in terms of what people do and don't do and so on.

However, when it came to the other instructors, many said that they don't have anything, or very little in the curriculum that covers muscle injury and prevention:

Currently we don't have a specific curriculum about injuries of the body.

Because like I say, in the last class I had, there was never a time period where we took two or three hours and I showed them, how to, you know, bend and lift, I mean you just don't do it.

There's a section prior to tools and equipment, and they discuss, you know, eyeglasses, personal protective equipment, basically, and in there, there's a section on the ergonomics of trowel size, stuff like that, but that's about the extent of it.

Overall, the instructors insinuated that the current curriculum is lacking and there's room for improvement:

I don't think we hit very hard at all. The Ontario Training Masonry Center.

The actual physical activity and working out and those types of things, probably… there's probably still a good… still lots of room for improvement, let's put it that way.

Conversely, while there was no material in the curriculum address muscle injuries and risks, most of the instructors still touched on the topic during their classes through informal teaching methods (62.5%), such as demonstrating techniques or correcting the apprentices' techniques:

When we teach how to spread mortar and pick up block, I teach what works for me and I've never had a problem, you know. So, I must be doing something right.

When I see people picking mortar up off their board with their trowel and they flick in the air for the suction I try to make my… I remind… I stop them and I tell them as many times as I can see them doing it, that the more you do that the more you're going to be pulling on that arm and I show them maybe just a light tap on the board instead and hopefully they understand that and then they go forward in the rest of level 1 not flicking in the air, maybe down the rest of their careers I might have saved their elbows.

Instructors also focus on muscle injury prevention by giving advice (75%) and stressing the potential long-term impacts of the trade:

I just give as much information as I can about what they could be doing to help themselves or making them aware that these injuries will exist and do *exist but again, as far as curriculum goes I don't have a… I don't think we've been given a chapter, you know*

So now it's a matter of taking that advice from a veteran like me that's been doing it for almost two decades and saying listen like you have to stretch you, you have to bend, you have to because otherwise you will pull a muscle and tear it.

I mean all the anecdotes I have, it's that you know, I used to jump off the scaffold at the top plank too and now it's every step down, you know, 'cause that… because people told me that, I didn't believe them but then eventually it catches up you. You know, just try to sound as crotchety as a bricklayer as I can and so they get that it's going to affect them.

All the instructors thought that material on muscle injury risks and prevention into the curriculum should be incorporated into the curriculum formally:

100%. 100%. Whether it's a few hours presentation or whether it's a day thing… like I don't wanna exaggerate it, but certainly like I say, the better off people are with anything they do in life, information is key ... we put so much emphasis on working at heights, we put so much emphasis on… WHMIS and with everything else… especially in the masonry field we should be putting emphasis, I feel, on your body, your muscles, you know, how they react.

5.3.8 Risk Modifiers and Safety Behaviours

Another major theme throughout the interviews were risk modifiers and safety behaviours. Risk modifiers were attributes that might increase or decrease an individuals' susceptibility to musculoskeletal injury. Similarly, safety behaviours are behaviours that masons would engage in to prevent musculoskeletal injuries. Analysis of these attributes and behaviours between and among apprentices and experienced masons revealed circumstances that might contribute to higher or lower risk of injury.

Experience was noted as one of the main factors affecting risk of injury (87.5%). This is likely correlated to revelation that one of the primary ways, masons learn about muscle injury risks and prevention is through personal on the job experience. As previously mentioned, instructors thought apprentices were at greater risk for injury is partly because of their lack of experience in the trade:

They're inexperienced, anyone inexperienced in any field is at risk to make a mistake, unfortunately in construction, mistakes can lead to injury.

I'd probably jump to the conclusion that the injuries are going to happen early on, in my view, 'cause […] they don't know their bodies as well as they will in three or four or five years.

Fitness and work conditioning were other factors associated with injury risk (75%). Instructors indicated that early on, not being conditioned to the physical demands in the trade could increase the risk of injury:

> *And they're just more open and more susceptible and parts of their bodies that haven't been worked in the way that it will be in our trade. Certain muscle groups that will now be exercised that perhaps were not exercised.*

> *On the other hand, instructors said that a level of personal fitness and conditioning that meets the job demands is protective and reduces injury risk:*

> *Staying physically active, staying physically fit is definitely imperative when it comes to masonry.*

> *I use the same set of muscles over and over and over, repetitively […] I guess I'm just used to the way I work […] the only time there'd be a problem is if you do something out of the ordinary, something you're not doing every day.*

Several instructors mentioned that anthropometrics (62.5%), such as body size and height, impacted masons' capabilities:

> *I think a lot of that has to do, there is --I hate to say this but there is a certain point where your physical size and your body type has a role to play in that. I have --again I have acquaintances who are in this trade and they are fairly large individuals like they're large frames. Like I feel they can stand up to the strains of laying concrete block on a daily basis, where I can do it for a few months, with my size --like I'm not small. I'm not big. I find that actually a lot of masons are around my size. Like I think I'm about 5'11", 180 pounds. Continually picking up a block again and again and again and again and again that weighs 65 pounds and then lifting it over a string to put it in a wall. I feel it at certain points depending on where the height is etc., kinda just like my extension, my range of motion. I feel it in my lower back. Just 'cause I do not feel I have the weight --the counterweight that block, because I'm just not that large.*

Technique also factored into susceptibility to injury (62.5%):

> *I think a lot of that came down to not doing things that I knew would contribute to that. So, the way that… you know, where I lifted objects from and how I move my body… lifting, you know, using the knee, keeping things close to my body, rather than away from my body, and it's those times when that wasn't possible that [injuries/pain] popped up again.*

The importance of warming up or stretching were also emphasized by a lot of instructors to reduce injury risk on the job site (50%):

> *I definitely let my younger and older students know, especially to be honest with you, the older ones… stretching is a known fact that if you don't stretch, you can easily pull something, tear something, and then you're really in trouble right. So yeah, I definitely promote stretching before you get to work, even stretching while you're at work, and then once you're into the job your muscles are nice and warmed up.*

Training (50%) and individual knowledge (37.5%) were also mentioned as factors influencing injury risk. Instructors noted that a lack of training or knowledge increases injury risk, which is often seen in apprentices starting the trade:

> *It really depends, I think on what you do, how that organization and your training. If you are properly trained, then I don't think [apprentices are more at risk to get injured].*

> *With no knowledge coming in, I guess, in fairness, you do stand a greater risk [to get injured]. Because you really don't know what you're going up against. When you see individuals, who are seasoned and what they do picking up these items that you have no idea what the weight is and just frankly maneuvering them with what seems like ease at times. I don't think it really kind of shows you what you're dealing with or the severity of the injuries that you can go up against.*

Awareness and attentiveness (37.5%) while working in the trade was also mentioned as a factor influencing injury susceptibility. Instructors noted that they had seen cases where a lack of awareness or attentiveness, especially in apprentices, lead to injuries:

> *You can literally tell them no you should bend your knees, keep your back straight, do this and then you turn your back, and you can hear someone scream in pain almost, because they just didn't pay any attention.*

On the other hand, they mentioned that their own awareness was something that helped them avoid injuries over the years:

> *I'm just aware of it, I guess. and I attempt to put myself--not put myself, I should say, in potentially detrimental positions.*

The equipment used was also mentioned by two masons (25%) regarding injury risk and prevention strategies. One mason mentioned that he kept a back brace on hand, just in case as a preventative measure, while another mentioned that his trowel type contributed to a wrist injury:

> *So, at first, I had the trowel, according to my foreman at the time, that put more pressure on my wrist. I switched and coincidentally, when I switched to the other brand, and the size, mind you, then my wrist injury sort of went away.*

Lastly, masons felt that susceptibility to injury depends on the individual, given the number of different factors that might influence it (25%). For example, some apprentices starting the trade may have a lack of experience, but more knowledge about proper movement strategies from previous experiences as an athlete or genuine interest.

5.4 Discussion: Ergonomic Knowledge and Attitudes in Masonry

5.4.1 Physical Demands and MSD Risk

The physical demands and MSD risks that instructors noted were in line with those frequently identified in the literature. In addition to the forceful lifting hazards of masonry blocks and bricks, repetitive motions were also a major concern for many of the instructors. When union and contractor representatives within the construction industry were asked about different ergonomic prevention strategies, one of the more consistent replies was increasing awareness of repetitive strain hazards and injuries (Boatman et al., 2015). Not only is repetition recognized by instructors as a hazard, but it is also important to amplify its consequences to apprentices when they are starting out in the trade.

A study on the prevalence of MSDs in masonry apprentices revealed that 78% of apprentices had symptoms associated with MSDs and these rates were similar to that of journeymen (Anton et al., 2020). Furthermore, this trend in MSDs was also found in other construction trades with apprentice floor layers reporting MSD symptoms at nearly the same frequency as more experienced workers (Jensen and Kofoed, 2002). This highlights that within the construction trades, and in masonry in particular, the problem of musculoskeletal pain starts early in the apprenticeship phase and extends throughout their career.

5.4.2 Impact of Physical Demands

The high rates of injuries in masonry and the construction industry are reflected in the personal experiences of the instructors. Despite a small sample size, several instructors reported injuries due to work demands. Previous studies have found that following MSD injuries, workers in the construction trade are less likely to return to work (Boatman et al., 2015). However, all the instructors interviewed, all having returned to work post-injury, sought some form of healthcare professional to help during the recovery process or did a form of self-rehabilitation. While some had to explore several different healthcare options, those that had a greater focus on the musculoskeletal system were more helpful, such as physiotherapists or osteopaths as opposed to general practitioners. In the experiences of the instructors interviewed, either changing equipment or proper rehabilitation was critical in allowing them to return to work and resume their duties injury free. The use of healthcare practitioners, especially those focusing on musculoskeletal rehabilitation, should be encouraged post-injury to aid the return-to-work process.

5.4.3 Safety Culture and Attitudes

5.4.3.1 Productivity

Productivity is a major driver of the industry, and this influence is seen in the safety culture. This is due to the pay rates of masons being based upon production, which was highlighted in the interview answers. Similarly, this view has been acknowledged in previous interviews of construction workers as one of the main obstacles to MSD prevention in the industry (Boatman et al., 2015). This underscores the need to discuss ergonomics within the framework of productivity, not only at the level of management and the return on investment but also at the level of the individual workers, who feel job pressures.

5.4.3.2 Injuries and Role of Industry

The culture and attitudes around safety in masonry were in line with other perspectives found in the literature from stakeholders in construction. For example, the instructors highlighted a belief in the trade that injuries are part of the job. This belief was also found to be held by other workers in the construction sector (Boatman et al., 2015). Furthermore, workers felt that their employers were not as committed to increasing workplace safety (Boatman et al., 2015). While this was not a theme in the interviews with the instructors, one instructor did have a strong sense of skepticism and cynicism when it came to the industry's role in improving safety. And instructors felt that the industry had a role in setting the expectations and contributing to the overall safety culture in the trade. In one study, organizational culture was purported to have a greater effect on construction workers' perceptions of risk than employer actions, and that construction workers were more likely to have little concern for the risks compared to other industries (Whysall et al., 2007). Instructors also felt that the training center for apprentices could do more to promote and teach ergonomics. Management commitment is one of the main barriers to ergonomic improvements (Fulmer et al., 2006; Yazdani and Wells, 2018). To improve the confidence of their workers, companies should demonstrate a commitment to employee health and safety, through time, resources, and other initiatives.

5.4.3.3 Socialization into the Industry

Other attitudes within construction such as personal pride, the drive to gain respect from their peers or the 'young and invincible' belief also contributes to the overall safety culture within masonry. Similarly, the pervasiveness of 'macho' attitudes in the construction industry has been mentioned as one of the barriers to cultivating a strong safety culture (Boatman et al., 2018). In construction trades, apprentices "are socialized into the workforce by their mentors and other older workers" leading many to adopt and reproduce the culture, attitudes, and habits of the older generations (Jensen and Kofoed, 2002). This can often lead to resistance to change, which is well documented within the construction industry, and poses a challenge to ergonomic interventions (Boatman et al., 2015; Entzel et al., 2007; Jensen and Kofoed, 2002; Yazdani and Wells, 2018). Resistance to change was touched upon briefly in the results with respect to resisting change to learned techniques. The influence of older workers and mentors on the apprentice during these formative years was highlighted by one instructor:

> *If you're getting into the trade, and you're already starting to do things the way Papa bear did it, and he did it the wrong way… well then guess what? He's setting you up for doing it wrong all your career.*

Masonry instructors mentioned the importance of training apprentices in early on in their careers during their skills training courses. This is also supported by other researchers who suggest that younger workers will be more open to learning new approaches (Boatman et al., 2018). To circumvent the challenges associated with resistance to change and pre-established beliefs and habits, ergonomics training should be target younger workers during their formative years before they are fully socialized into the trade.

5.4.3.4 Shift in Attitudes

Despite beliefs that ergonomics within the industry and the training center could improve, instructors highlighted positive changes in the industry over the last decade. This belief was also held within the construction industry as well (Boatman et al., 2015). This may signify that despite existing attitudes in the industry, the overall culture is shifting towards a more positive emphasis on safety and ergonomics. In the interview results, while many instructors noted that the 'young and invincible' attitude was ubiquitous amongst the younger workers, one instructor said that the incoming generations are much more concerned about ergonomics and safety and that it was one of the most frequently asked questions in their outreach programs. This demonstrates that despite continuing attitudes in the trade, overall, there may be a slow shift towards increased attention towards safety with the incoming generations. Boatman et al. (2015) state that the improvements in technology and tools as well as increased focus on training and awareness is leading the cultural shift.

5.4.4 Education and Training

Training and knowledge were identified by instructors as factors influencing injury risk in apprentices. Lack of awareness, knowledge or training about MSDs and ergonomics are also critical issues affecting MSD prevention in the construction industry (Boatman et al., 2015; Entzel et al., 2007; Gervais, 2003; Jensen and Kofoed, 2002; Kincl et al., 2016; Kramer et al., 2009; Yazdani et al., 2018). These include a lack of awareness of the significance of MSDs in the industry, an understanding of MSD risks and long-term consequences and costs, and basic ergonomics principles (Boatman et al., 2015; Gervais 2003; Kincl et al., 2016; Kramer et al., 2009; Yazdani et al., 2018). In the US, 44% of Hispanic construction workers reported no formal safety training despite 67% indicating a high interest in safety training (McGlothlin et al., 2009). Ergonomics training is often lacking in apprenticeship programs as well (Kincl et al., 2016). This idea was also shared by the masonry instructors in their interviews about the inclusion of ergonomics information in their curriculum. Researchers agree that ergonomics training should be included at the apprenticeship stage (Kincl et al., 2016; Jensen and Kofoed, 2002). Jensen and Kofoed (2002) emphasize that experienced individuals in the trade should disseminate the knowledge in order to break down resistance to change resulting from the socialization of apprentices into the workforce. The use of experienced individuals allows these instructors to approach the apprentices with a level of credibility and respect, speak from experience, and communicate using the language of the trade. This sentiment was also shared by the instructors in the second half of the interview. Training should be practical and tailored to the context of the trade, include awareness and refresher training and apprenticeship training should be reinforced on the jobsite (Entzel et al., 2007; Gervais, 2003; Marras and Karwowski, 2006; Abdul-Tharim et al., 2011). For masonry training, Entzel et al. (2007) suggest the inclusion of information on the job site layout, ergonomic tool use, mortar spreading technique, lifting, and adjustment of mast climbing work platforms and adjustable tower scaffolding. From a behavioural change perspective, interventions in construction should target the audience's particular stage in the stages of change model for the highest probability of effectuating individual behavioural change (Village and Ostry, 2010). More specifically, in the precontemplation stage, information about MSD risks should be provided (Village and Ostry, 2010). In the contemplation and preparation stage, further education about MSDs and awareness of action items should be provided (Village and Ostry, 2010). Lastly, in the action stage, practical training, skills, and advice should be provided (Village and Ostry, 2010).

5.4.5 Knowledge Sharing

Knowledge sharing between coworkers and from the older generation to the younger generation is critical to the learning experiences of masons and this transfer of knowledge is highlighted in the instructors' experiences regarding MSD prevention techniques. In the literature, the social interactionist model of knowledge transfer suggests that not only is knowledge social but that it is formed within a social context (Kramer et al., 2009). This theory reinforces the importance of peer-to-peer communication as a method of knowledge sharing within the industry. To further emphasize the role of social communication for the lack of a forum to share knowledge about interventions was found as a barrier to the promotion of ergonomics within construction (Fulmer et al., 2006; Kramer et al., 2009). A study on the adoption of an ergonomic intervention spread through knowledge transfer and exchange found that the use of opinion leaders (credible and connected individuals) within the construction industry could promote adoption of ergonomic interventions (Kramer et al., 2009). The practical, onsite experience of the opinion leader was valued by their peers when it came to judging the adoption of the intervention. The study showed that ergonomic change could be driven in part by a select number of key leaders and word of mouth. This mimicked the natural process of knowledge sharing that the masonry instructors highlighted in their interviews, as one of the primary ways of learning about risk prevention strategies besides experience.

5.4.6 Risk Modifiers and Safety Behaviours

Previous studies have reported that to prevent MSDs, construction workers engage in "exercising and conditioning, getting better tools and adapting tools to make them easier to use, wearing braces and pads, self-medicating with Motrin or Advil, attempting to rotate tasks or switch hands, and getting educated and talking with others" (Boatman et al., 2015). Tool, material and working technique changes are also advocated as a method to reduce MSD risk by Jensen and Kofoed (2002). All these safety behaviours and strategies were also reflected in the interviews with the masonry instructors as ways to manage the physical demands and MSD risk.

5.5 Summary

The instructors' exposure to high physical demands within masonry was a major theme during the interviews. Instructors discussed the high forces, repetition and awkward postures which take a toll on their bodies. They also mentioned their reduced physical capabilities in response to the job demands as they age. Furthermore, instructors mentioned how consistent exposure to high demands led to various injury experiences and how they dealt with them. Several instructors had never been injured.

Another large theme was about the safety culture and attitudes within the trade. Younger apprentices often think themselves invincible and show less concern towards musculoskeletal safety, whereas the older masons are more concerned. Perhaps this is a contributing factor into the difficulty of getting the apprentices to take safety seriously. Productivity also plays a role in the safety culture. Productivity is sometimes prioritized at the expense of safety. Some masons view injuries as part of the job, despite instructors noting a shift in attitudes from the industry regarding safety on the job. The industry also plays a role in the safety culture since they set the working expectations. Furthermore, trying to gain respect or impress, pride, taking the easiest route and the instructors' individual perceptions affect safety attitudes and behaviours. Masons learned about muscular injury risk and prevention strategies from knowledge shared by other masons or experience. When the instructors were apprentices, the level of ergonomics training spanned between little to none to moderate. Some instructors noted that the current curriculum has more information available for apprentices, but many instructors still said that there was little to no material on ergonomics and lots of room for improvement when it came to training about ergonomics. Most information on ergonomics was shared informally during as demonstrations, corrections, or advice, etc. All instructors thought that ergonomics training should be integrated formally into the curriculum. Lastly, factors that influenced the level of risk or safety behaviour by masons included experience, fitness or work conditioning, anthropometrics, technique, warm up or stretching, training and knowledge, awareness, equipment, and individual factors.

5.6 Insights and Recommendations

- Physical demands in the masonry trade contribute to higher MSD risk and general wear and tear on the body.
- As masons age, their injury risk also increases given their reduced strength capacity
- Many of the masons will get injured during their career, and this is reflected in the high injury rate in masonry.
- Masons should be encouraged to seek help from healthcare professionals post injury to help with the rehabilitation process and return to work if necessary.
- However, injury can be prevented through practicing good safety behaviours.
- There is a belief within the trade that injuries are just part of the job; however, those beliefs as changing over time as technology helps reduce injuries and more safeguards or preventative actions are taken.
    - Industry leaders play a role in stressing the importance of safety, especially through setting expectations.
    - Implementing a formal program on ergonomics can help contribute to an overall culture change within masonry that injuries can be prevented.
- Often young masons will believe they are invincible; therefore, the long-term cumulative damage needs to be directly connected to their present actions.
- Apprentices may lift past their capacity because of: (1) pride, (2) desire to impress, (3) respect for leaders, (4) laxity, or (5) pressure for speed/productivity.
    - These should be highlighted as pitfalls to avoid.
- The reduced productivity of working past your physical capacity should be stressed; similarly, the reduced productivity of becoming injured should be highlighted as well.

    - Ergonomics should be discussed within the framework of productivity.
- Discussions about ergonomics should be encouraged among masons.
- Expert masons are critical in exchanging knowledge to the younger generation, not only as a way of learning but also due to the respect the apprentices have for them.
    - The best way to get the message through about safety may be through advice and anecdotes from expert masons who have gotten injured in their career.
    - Instructors should be encouraged to talk about their own experiences with injury and have discussions with the apprentices to share their knowledge.
- Improved fitness, warming up, stretching, technique, knowledge and training, equipment and awareness and attentiveness can reduce the risk for injury in apprentices.
    - Training and knowledge can be increased through formalized training on ergonomics and techniques.
    - Technique can also be improved through training.
    - Instructors should discuss equipment within the training program.
- Warming up and stretching should be encouraged within the training center and within the industry.

5.7 Results: Training System Feedback

The thematic analysis map (Figure 48) outlines the themes and subthemes identified in the interviews regarding feedback on the proposed training system. These themes will be discussed in further depth in the following results section.

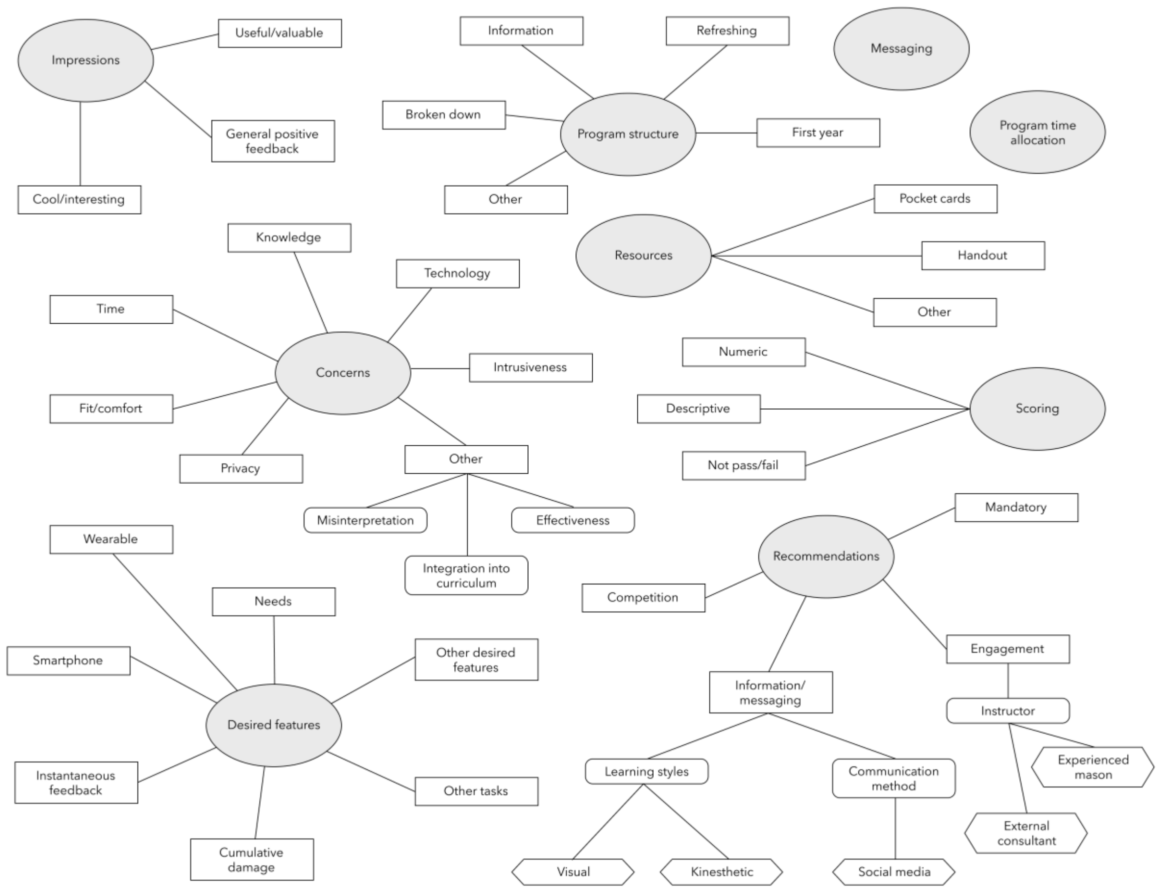


Figure 48: Thematic Analysis Map for Training System Feedback

5.7.1 Impressions

All the instructors interviewed had positive overall impressions about the proposed training tool and program. All instructors (100%) indicated in some means that they thought the tool would be useful, beneficial, or valuable for the apprentices:

> *On my end of things, I'm appreciative of what you guys are doing because it --again I personally think it will make the difference between someone doing this for a long, long time and being crippled from it or doing it for a long, long time and then actually being able to enjoy your retirement, right.*

The most common general impression noted by most instructors (62.5%) was that the tool was "cool" or "interesting". Other positive remarks referring to the training tool and program included "phenomenal" and "ground-breaking".

5.7.2 Concerns

The major categories of concerns mentioned by the instructors were time demands, knowledge requirements, complexity of the technology, fit/comfort, intrusiveness, privacy, and others.

One of the primary concerns among instructors (37.5%), and particularly stressed by the director of training, were the time requirements to set up and use the tool. The tool must be simple to use and not time consuming, otherwise the instructors will not have the time to use the tool since they must dedicate their time for the rest of their curriculum:

> *Time is probably the biggest factor in anything. We don't have unlimited amount of time and so if anyone… new initiative seems to be one to take a huge amount of time then nobody really is that interested in buying into it.*

Given the number of students in a class, the instructors would only be able to set aside a small amount of time for each student to run the assessment; therefore, they would not be able to monitor the tool for the duration of the assessment. These time constraints should be considered when designing the training program and determining whether it is feasible for the instructors to conduct the assessment, or whether an independent party should be hired to conduct them. Some instructors were a bit hesitant with regards to the knowledge requirements for both the teaching material and the technology use. Instructors wondered if they had the right expertise to teach the material, which they might be a bit unfamiliar with at first:

> *We might be under qualified to speak to that, right. You need to get an uh grad student that's studying the anatomy to really articulate the pros and cons of doing things in certain ways.*

The technological complexity was also a concern it was noted that older instructors might have a difficult time due to lower technological literacy. Overall, the technology aspect must be as straight forward as possible with clear instructions on how to use and troubleshoot:

> *I mean if it takes too much trouble for us or if it's you know if it's a job unto itself to use it and it is overly complicated or time consuming, it's not going to be something that's appealing.*

The fit or comfort of the device was another concern noted by 2 instructors (25%). This included concerns over the inclusivity of the sizing of the device, and whether the wearable sensors might get warm and cause discomfort. Several instructors (37.5%) raised concerns over the intrusiveness of the wearable sensor suit while working. For example, if there were wires that impeded movement in some way:

> *Unless it got really hot or something, you know, I don't know what… it's just wires or if it's going to be something that, you know, it's hard to work around like… I have these wires dangling and when I go to get my trowel and more important the wires are restrictive or whatever.*

However, one instructor mentioned that even if the suit was a bit uncomfortable or intrusive, it would be comparable to wearing a safety harness on a job site and would only be temporary. Two instructors (25%) indicated that privacy and personal space might be a concern, either if other people had to put the suit on them, or with the idea of having sensors on their body:

> *Well unless somebody has some issues with their you know their body being intruded with… with whatever device you put on.*

However, this concern could be alleviated given they could put the suit on themselves, and that they had the right to refuse participation. There were a few other concerns that weren't brought up by multiple instructors, but they included concerns over the effectiveness of a behaviour-based intervention, ease of integration into the curriculum and whether apprentices will misinterpret or misconstrue the advice of the tool and program.

5.7.3 Desired Features

The instructors need a tool that is user-friendly and easy to use. It should be simple and have clear directions for use. In terms of desired features, the several features that came up repeatedly were improving the wearability of the suit in the form of a shirt etc. (25%), integration with a smartphone app for the apprentices and instructors (50%), instantaneous feedback via audio, vibration etc. (37.5%), making direct connections between risky postures and cumulative damage or outcomes (37.5%) and including other everyday tasks in the assessment such as working with the trowel arm, collecting mortar from the mortar box etc. (50%). Other desired features that were only brought up by one individual include integrating other factors on the work site that contribute to risk such as weather, job pressure etc., syncing and superimposing the apprentices' movements with the correct movements on a smartphone or a VR device, and visually showing the joint stresses with the correct movement beside the incorrect movement.

5.7.4 Recommendations

The instructors gave an insight into the type of information and messaging to use when delivering the training program to the apprentices. Information that should be included in the program is the purpose of the training program, how the tool works, past data collected from the tool, the importance of technique and long-term benefits. One instructor also suggested integrating stressing the importance of regular checkups with a healthcare physician. In terms of the messaging, the instructors said that it is critical to highlight the value in the training program and how they will personally benefit from it, as well as tailoring the messages to their individual interests and personality to make it more relatable.

> *Well, I don't use a blanket approach because everybody is different and that saying about different strokes for different folks… there's some truth to that. And I just use the technique on the individual that I believe is going to work on that individual. And you know I switched up… I have 10 kids right now or 10 people in my class… some are married, some have kids, and some are purely single, and I treat them all the same but differently, if that makes sense. You know I don't talk to… let's say the mature guy who's got a kid the same way as I talked to the guy who's looking to for a club on Saturday night. They're different conversations and they're different ways in which I speak to them.*

Above all, instructors should be honest and genuine when speaking to the students. When it comes to different ways of relaying the information and learning styles, almost all instructors emphasized visual mediums (87.5) followed by hands on approaches (87.5). Visuals, such as presentations, videos, and demonstrations as well as practical exercises in the shop were all suggested teaching methods for the training program:

> *You certainly don't wanna talk to them for any more than 20 minutes in front of a class, you want to get some visual materials up there.*

Lastly, one instructor suggested the use of a social media page to better communicate information, reminders, and updates and to foster an online community. Engagement was stressed as critical to the success of the training program:

> *You have to keep it brief and packed with as much …action packed as possible. Like as much stuff to grab their attention as possible.*
>
> *The flashier it is, the more likely it's going to be successful.*

Often, the level of engagement ends up in the hands of the instructor delivering the information, as noted by two individuals. Along the same lines, there were conflicting opinions among the interviewees among who should deliver the information. Two instructors suggested that an experienced or expert mason would be the best instructor, since they would be able to speak from experience and command credibility and respect from the apprentices:

> *We have with courses in this in the school that students take part in and of course the instructor like myself stands at the back of the class, and we can participate as well and we will do IHSA courses, you know… some of these guys, the first thing they say is, you know… Oh I used to be an electrician for 20 years or I used to be a pipe fitter or I used to be a plumber… right off the hop, you know that --that level of respect just kind of gets there because you're like, OK this guy obviously, clearly knows what he's talking about, because he's been doing it for the last 20 years, right.*

On the other hand, two instructors suggested that due to the content of the material (health and ergonomics), they felt it was outside their area of expertise and that perhaps an external consultant that was more knowledgeable on the topic would be better able to articulate the important points and explain things thoroughly:

> *I know where the line is right, and I don't know if I'm crossing into a territory that perhaps it's not an area of my expertise. Like even in our shop, in the eight weeks that I'm there, we bring in industry experts that perhaps could deliver information and material in a way better than I can, since that's what they do every day. Like do you know what I mean? Like… like I can talk to it but not in the same way, into the same effect as they can.*

Two instructors mentioned that the apprentices like to challenge each other so implementing a game or competitive aspect might increase engagement. Lastly, two instructors said that for safety training to be taken seriously, it needs to be mandatory or there needs to be more rigid consequences associating their safety performance with their work performance.

5.7.5 Program Time Allocation

The instructors were asked how might time they would allocate to teaching about ergonomic risks and injury prevention during their apprentice training courses at level 1, 2 and 3. This gave insight into how valuable they thought teaching this topic would be, as well as a guide for how long instructors thought would practical to spend on the topic. On the other hand, the time allocation guidelines set by the director of training was the highest priority feedback, given that he managed the training program and set the requirements that the instructors followed. Of interest, the director of training took a more managerial approach to the training tool feedback section of the interview, as indicated by the greatest concerns about time allocation compared to the other instructors. The director of training was able to provide valuable insights into the overall constraints on time, and the maximum time that could be allocated to ergonomics training at the different training levels. In essence, while the acting instructors gave suggestions, the director of training provided the upper limit for allowable time.

For 1st year apprentices, the maximum time would be a total of 7 hours and at level 2 and 3, there would not be time for more information, but rather just refreshers and redoing assessments with the tool. Most of the instructors indicated between 2 to 4 hours should be dedicated to it at level 1, with one instructor saying a full day (estimated to be around 7 hours). Of those 2-4 hours, a portion of it would be dedicated to class time with the rest dedicated to practical application in shop. Instructors said that less time should be allocated in level 2 and level 3, with a focus on refreshing the information or following up with skills learned.

5.7.6 Program Structure

In terms of program structure, several instructors recommended the content and practice be spread over a couple days (50%). Instructors (50%) emphasized the importance of teaching the apprentices about muscle injury risks and prevention strategies starting in level 1, since they are just starting to learn the proper techniques, which will set them up for the rest of the levels and their career. In the subsequent levels, the apprentices will need refreshers to remind them of the training material. Instructors should give the students information in an engaging way and pair it with demonstrations and hands-on and practical ways to implement it in the shop. The types of information that instructors mentioned the training program should include are ways to identify if an apprentice is improving or where they have gone wrong, the daily musculoskeletal risks on the job, preventative warmup exercises and stretches, and lifting techniques. Other suggestions for program structure included morning calisthenics or warmup exercises and initiating a discussion in the group about personal experiences with musculoskeletal injuries and how to prevent them. Lastly, the training director indicated interest in a personalized assessment using the training tool at the beginning of the 8-week course and at the end to measure improvement.

5.7.7 Messaging

There were no specific questions targeting the type of messaging that would most resonate with the apprentices besides the method of communication; however, several instructors brought up the way they framed ergonomic safety to emphasize its importance to their apprentices. One instructor compared the physical demands of work, especially when lifting heavy loads, to going to the gym, where you would warm up properly and use proper form to avoid injuries. Another instructor used anecdotes of personal stories to relate the consequences to the apprentices, such as asking them if they knew anyone who suffered an injury and then telling them the story of a worker, they knew who suffered a serious injury and the outcome of that individual. Another instructor chose to emphasize the cumulative effects of the physical demands and how they can result in MSDs when they are older. He also emphasizes the importance of safety so that the apprentices can keep their health and enjoy their life fully:

> *My exact line to them in the course is that if you go through your career and you put your time in, so you can retire and then by the time you get there you can't walk because you destroyed yourself, what was the point? Because that's how I look at it. I use the same speech for safety gear, like safety glasses and earmuffs and things like this. I try and if I know the students, once I get to know them, I'll try and get --key in on their hobbies and their likes… try to say like, you like to do this, yeah, you know there's no point in even making money if you can't do what you wanna do afterwards. Sometimes I'll throw in like, what I like to do, right, if they get to know me, I'll use one of my hobbies as an example. Like if I can't do this because my… I slipped three discs in my back picking up a rock that was the size of me then, what was the point? It wasn't worth it.*
>
> *Lastly, one instructor also mentioned that he discusses ergonomics within the framework of productivity and their performance in the eyes of their employer:*
>
> *It doesn't favor your employer to do so and I try and explain that to them, that you hurting yourself only costs them more money and frankly even to the point where you overworking yourself doesn't favor them. If your output drops by 35% each day past Tuesday, because you're so sore and exhausted, you're no good company. […] Again, don't overwork yourself 'cause you're not helping your employer. Nobody wants to pay masons double time on overtime, to lay 1/3rd of what they were laying in the morning, or producing, if you will.*

5.7.8 Resources

A variety of resources were suggested as options for additional training aids for the students. Pocket cards were the only resource that was brought up by several instructors (25%). The instructors noted that the apprentices already receive pocket cards for other areas of safety such as hoisting and rigging, working with a crane, hand signals, etc. and therefore would fit in well with the rest of the safety training topics. Pocket cards would be small visual reminders that could always be stored in wallets and kept on the apprentices. Having a place to be stored might reduce the likelihood of the apprentices misplacing the cards. On the other hand, several instructors noted that handouts would be ineffective and lost or misplaced by the apprentices.

Other types of resources suggested as one-offs by the instructors were USBs with information, a poster, a social media page, a physical trainer and literature for the instructors.

The stakeholders at CMDC and the director of training at OMTC expressed interest in having a poster for the training center with information about warming-up and stretching.

5.7.9 Scoring

When it came to providing a scoring metric for the apprentices, almost all instructors (87.5%) preferred a numeric score by joint over a whole-body numeric score or a simple pass/fail system. The instructors preferred a score broken down by body area, since it would be able more information about the risky posture and would therefore be more meaningful. Instructions specifically noted that a pass/fail system would be detrimental because the apprentices would then perceive all actions that didn't meet the passing threshold within the same category of a 'fail' despite considerably varying risk levels. From a practical point of view, an instructor noted that the apprentices will do a lot of 'risky' behaviours regardless and that using a numeric grade will enable them to make their own decisions on which risky behaviours are more tolerable and which should be taken seriously. Two instructors (25%) indicated that a more descriptive system should be used, with either a colour code or descriptive words to convey the risk in a simpler and easily relatable manner.

5.8 Discussion: Training System Feedback

5.8.1 Impressions

The instructors all had positive impressions of the tool and were on board with implementing formal ergonomics training into the apprentices' curriculum. They also thought ergonomics training was very important and valuable to teach the apprentices about. Other studies also report positive attitudes and interest from construction workers about ergonomics training to prevent MSDs (Boatman et al., 2015; McGlothlin, et al., 2009). Many construction workers in the trade are open and receptive to information and training on ergonomics.

5.8.2 Recommendations

Among the various recommendations from the instructors on the ergonomics training program, two instructors thought that safety training needed more rigid consequences tied to their work performance. This sentiment was also reflected by other stakeholders in masonry. Representatives at a 2-day meeting to discuss best practices to prevent MSDs in masonry suggested that safety needed stronger enforcement of policies related to safety, and even sanctions for unsafe workers (Entzel et al., 2007).

5.8.3 Program Structure

When it came to ergonomics, instructors emphasized the importance of stretching and warming up as well as the role of technique and training in preventing MSDs. While instructors also mentioned other strategies such as the impact of equipment and collaborative lifting on reducing MSDs, none of the instructors discussed ergonomic assessments or changing the workplace in response to MSD risks. This shows that the level of knowledge on ergonomics of the instructors and within even experienced journeymen, usually lies at the level of administrative controls rather than engineering controls. In an efficacy study on an ergonomic intervention in the construction industry, over 90% of workers applied some or a lot of information about body conditioning and stretching and safe lifting techniques (Hecker et al., 2000). Workers were less likely to apply information about the identification of ergonomic risk factors and solutions; however, almost two thirds of the workers said that they had made ergonomics changes (Hecker et al., 2000). Construction workers may find it easier to apply the administrative controls such as stretching and lifting practices because it involves individual behavioural change rather than ergonomic changes which may sometimes affect everyone on the worksite and require additional steps to get something approved. Furthermore, applying ergonomic interventions on construction sites is difficult due in part to constant changing of the worksite (Kramer et al., 2009; Hecker et al., 2001).

Researchers support the inclusion of ergonomics training at the apprenticeship level (Albers et al., 1997; Hecker et al., 2000), but stressed that training at the apprentice level alone is inadequate, and that ergonomics training should also be provided at all stages of one's career (Hecker et al., 2000). This highlights a need for ergonomics training to continue on the job site past the skills training courses to reinforce the importance of safety within the working environment and refresh the information through one's career. This is more important given the findings that as the apprentices age, not only do their attitudes about ergonomics change, and they are more likely to care about muscle injury prevention, their physical abilities also diminish, which may increase their overall risk of injury.

Furthermore, research suggests that ergonomics training programs should be learner-centered, participatory, and job or trade-specific within the construction industry (Abdul-Tharim et al., 2011; Albers et al., 1997; Choi, 2012; King et al., 1997). For ergonomics training during the apprenticeship phase, the programs should be integrated with their shop classes for skills training (Albers et al., 1997), which is the goal of our proposed training program. In a study of ergonomics training efficacy, lecture, or participatory training in addition to ergonomic job redesign resulted in increased job satisfaction compared to a lecture only group and a control group (King et al., 1997). To maximize learning potential, programs should incorporate active problem solving rather than solely lecture based learning, which ties into adult education theory (King et al., 1997). Ergonomics training programs should include awareness training and refresher training (Marras and Karwowski, 2006; Abdul-Tharim et al., 2011). The basic tenets of awareness training with respect to ergonomics are to understand ergonomics principles, risk factors, early indicators of injury, the medical management system, their participation in jobs analysis and their roles and responsibilities (Abdul-Tharim et al., 2011).

Furthermore, a study on attitudes of contractors, union representatives and workers in the construction industry outlined several components for a successful ergonomics campaign within the industry (Boatman et al., 2015). These components include documenting cause and effect relationships, standardizing terminology without using the word ergonomics, developing separate campaigns for contractors and workers, developing contractor success stories, addressing resistance to change, and including explicit framing of ergonomics (Boatman et al., 2015). While these suggestions were proposed as best practices for a social marketing campaign to promote ergonomics in the industry, many of the findings can be applied to our training program and modules. Within the framework of our ergonomics training program, we can apply several of these practices. The training tool itself will be able to show postures directly associated with whole body or joint scores, and the resulting scores can act as markers of learning for the training modules. Once the training program is validated, it will be able to demonstrate the risk-related outcomes following implementation. In the instructors' interviews and the training module materials, the term muscle injury and muscle injury risk and prevention were chosen as a standardized term to avoid the use of the word ergonomics. The term muscle injury is easily understandable to the public and places MSDs on the same level as other injuries that are often the focus of health and safety training such as cuts or falls etc. Both the training tool and program were developed with the perspectives of masonry stakeholders and journeymen's expertise. This process not only tailors the program to the workers and makes use of success stories and peer to peer messages, but it may also reduce resistance to change since it incorporates the working methods of the older generation of workers. Lastly, the program aims to frame the discussions of ergonomics within the context of productivity to increase the buy in from the workers and stakeholders.

5.8.4 Resources

With respect to resources for training material to be disseminated to workers, stakeholders in the construction industry offered similar suggestions to the instructors. Stakeholders suggested websites, videos, tip sheets and even ergonomic handbooks (Entzel et al., 2007). This was in line with the suggestions from the instructions about the importance of visual communication and even the suggestion of communication through social media. However, instructors had lower confidence that paper handouts would be kept or read by the apprentices. Therefore, in the context of the masonry skills curriculum, information on tip sheets would better be communicated in the form of pocket cards.

5.8.5 Messaging

Instructors conveyed the importance of safety to the apprentices by highlighting their health, their quality of life, making it personally relatable by using anecdotes or mentioning their hobbies and lastly, by framing ergonomics within productivity and the employer's interests as well. These themes aligned with themes found to resonate in the literature. A study researching stakeholder perspectives on ergonomics in construction, found that the top safety messages that would resonate with construction workers were to adopt safety practices for their family, to avoid excess expense, for their health, and for productivity (Boatman et al., 2015).

5.9 Summary

All instructors had positive overall impressions about the proposed training tool and program. General feedback included that it was useful or valuable, and that it was cool or interesting among other positive comments. Concerns for the use of the tool included time requirements, level of necessary expertise, technological complexity, fit or comfort, intrusiveness, and privacy, among others. Instructors wished for the end product to be simple and easy to use. Desired features included improved wearability, smartphone connection, instantaneous feedback, feedback about cumulative damage, assessment of other masonry tasks and some others. Instructors recommended using primarily visual or hands-on styles for teaching the apprentices and one instructor recommended social media to connect with the younger generation of apprentices. Furthermore, engagement was stressed as critical to the success of the program and the instructor teaching the course has a large impact on that. Instructors thought that either an experienced mason or an external consultant should teach the course on ergonomics. Additionally, to help the buy-in among the apprentices, the program could leverage the competitive culture between apprentices or make the intervention mandatory. The instructors recommended that the program take 2-4 hours at level 1 and less time at level 2 and 3. However, the director of training indicated a maximum time allocation of 7 hours was possible at level 1, with only time to refresh the information at level 2 and 3. For the program structure, instructors recommended breaking down the content and separating it into smaller chunks, making sure to teach the fundamentals during the first level and refreshing the information in the later years. Instructors emphasized the apprentices' health, quality of life, and productivity to convey the importance of safety to apprentices. Instructors suggested that pocket cards could be created as an additional resource for apprentices, but that handouts should be avoided. For the scoring system within the tool, a numeric scoring system that breaks down the score by body parts was preferred with additional suggestions of a descriptive and colour-coded system.

5.10 Insights and Recommendations

- Concerns
    - The tool should not take a lot of time for each student.
    - The tool must be user-friendly and simple to use with clear step by step instructions.
    - The device needs to be able to fit all body types and students should be able to put the suit on themselves or have the option to decline participation.
    - Instructors should be educated on the suits so that they do not have concerns about the fit/comfort or intrusiveness of the device.
    - An external consultant should be hired to run the assessments and interpret the data for the trainers.
        - Solves concerns about technical, knowledge and time requirements.
- Desired features
    - The tool should make direct connections between risky postures and cumulative damage or outcomes.
    - Future work should focus on instantaneous feedback, integrating the training with visuals such as AR and connections to smartphones.
    - The tool should also be expanded to make recommendations and feedback for other masonry tasks in the future.
    - A future iteration of the tool should also consider purchasing a wearable clothing item to house the sensors for improved wearability.
- Recommendations
    - The training program should include information about the purpose of the training program, how the tool works, past data collected from the tool, the importance of technique and long-term benefits.
    - Regular check-ups with physicians should also be encouraged.
    - The training program should highlight the value of training and how apprentices will personally benefit from it.

    - The program should tailor messages to the individuals for better impact.
    - The program should focus on visual or hands-on means of teaching and communication.
        - E.g., images, presentations, videos, demonstrations, and practical exercises.
    - A social media page could be helpful to communicate information with students.
    - The training program needs to be engaging.
    - An expert mason would be able to earn credibility and respect from the students, but an external consultant might be better for teaching more technical knowledge.
    - The program could leverage the competitive culture among the apprentices.
    - Ergonomics training should be mandatory so that it is taken seriously.
- Program time
    - Maximum of 7 hours for the training program at level 1, no additional teaching in level 2 or 3, just refreshers and assessment.
    - Introduce the information and fundamentals to the students at level 1.
    - Follow up with refreshers at levels 2 and 3.
- Program structure
    - Break down the content to spread across different days.
    - Personalized assessment at the beginning and end of the 8-week course.
- Messaging
    - Health and quality of life.
    - Discussing ergonomics within the framework of productivity.
- Resources
    - Pocket cards for lifting techniques.
    - Pocket cards and a poster for warm up exercises and stretches.
- Training tool
    - Numeric scoring system by joint accompanied by colour code and descriptive words.

Chapter 6
Development of Training System

6.1 Design Brief

6.1.1 Company Profile

The Canadian Masonry Design Centre (CMDC) acts as a liaison between the masonry construction industry and designers through research, education, and technical support. Key stakeholders include CMDC, the masonry instructors from the Ontario Masonry Training Center (OMTC), and the masonry apprentices themselves. CMDC provides technical support during the research and design phase while the instructors are the end user, and the apprentices are the target audience.

The goal of this project is to create ergonomic training resources to reduce MSD risk in masonry apprentices. The project will include a redesign or updated design of the onsite assessment tool, including up-to-date research findings and analyses. The project will also include the development of in-class ergonomic training materials for instructors and students as well as a guideline on how to carry out the program. The provided materials will cover training and possibly other administrative controls relating to masonry. Specifically, the postural or technique training will only encompass recommendations for the standard wall (pick-up/transfer/lay-down) because of the research background on the standard wall at this phase of the project. Recommendations for lifting above shoulder height is not included in the scope of this project, and the program can be expanded to include other tasks in the next research phase.

6.1.2 Target Audience

The target audiences are the masonry apprentices (levels 1 through 3) and the masonry instructors depending on the deliverable. For the in-class teaching materials e.g., the PowerPoint presentation and the worksheet, the end user will be the instructor, but the audience will be the apprentices. Similarly, for the onsite assessment tool, the audience will be the apprentices, but the end user will be the instructor. All accompanying materials supporting the use of the onsite assessment tool will have an end user and audience of the masonry instructors who will have to set-up and implement the tool. Overall, the project deliverables must work for the instructors as teaching tools; however the in-class content and tool itself should be designed for the apprentice needs. Support materials should be designed with the instructors in mind.

6.1.2.1 User synopsis: Instructors

All instructors are experienced journeymen. Most instructors are older males who have worked in the industry for a long time. Most have limited computer use and competency. Instructors will use the teaching resources to teach the apprentices during the 8-week apprenticeship course. Instructors will operate the onsite assessment tool to evaluate the students at the beginning and end of the course and provide feedback and score. Due to the structure of the program, one of the most important considerations for instructors is the time requirement of new interventions because there is not a lot of time available. Easily integrated programs that are not time consuming will have the best buy-in. Not all of the instructors have a lot of technological competencies; therefore the tool should be as simple as possible to use with step-by-step instructions. When it comes to ergonomics and muscle injury risks and prevention instructors will have a fair amount of know but are not experts. They would know the main ergonomic risk factors (force, posture, repetition, and duration) and that manual handling activities such as lifting, pushing, pulling can lead to muscle injuries. They would likely be able to recognize ergonomic risk factors and suggest different prevention strategies to eliminate or reduce ergonomics risks on the job site.

6.1.2.2 User synopsis: External Training Consultant

Given the time, technology and expertise concerns of the instructors, an external training consultant should be employed to run the assessments and interpret the data for the trainers. The external consultant should have knowledge of the tool itself, the sensor technology and troubleshooting methods as well as biomechanics knowledge to interpret the outputs and relay the information to the students or instructors. The consultant should also have ergonomics and biomechanics knowledge to help with instruction of the ergonomics course or training, as necessary.

6.1.2.3 User synopsis: Students

Students have varying levels of experience when the take the courses, because blocks of practical experience are required between each level. There are 3 levels of courses total. Different students will take longer to gain that practical experience between 3 to 5 years to complete the entire apprentice duration and challenge their red seal. Students taking the 1st level will usually have a full year of experience working with a contractor or may entry through the pre-apprenticeship program and have no prior experience except in the program. Most students in the program are males in their 20s. Based on previous data collection, the average student is 26 years old, 181 cm in height and 88.1 kg in weight. The goal of the students is to successfully complete their 8-week skills course. Students will learn ergonomics and training concepts from the instructors during the 8-week apprenticeship course. Students will be assessed using the onsite evaluation tool at the beginning and end of the course and receive feedback and score. The training program needs to be engaging to appeal to the younger generation. Students are more concerned about their bodies and whether they will be able to sustain the workload as a mason. Apprentices have a sliding scale of knowledge when it comes to muscle injury risks and prevention in masonry. First and second year apprentices will know very basic things about muscle risks, while third- and fourth-year apprentices will know about the main ergonomic risk factors. Similarly, most apprentices will only know basic things about injury prevention, with more experienced apprentices having more knowledge. Overall, all apprentices may have difficulty recognizing at risk activities in the workplace and suggesting strategies to eliminate or reduce risks on the job site.

6.1.3 Design Requirements and Constraints

For the onsite assessment tool, the total time spent on evaluation per student should be as little as possible, ideally not exceeding 15 minutes, including donning equipment, calibration, assessment, input, and results. Ideally the instructor would be able to set up the equipment and not have to monitor it for the entire time. If the monitoring and assessment portion becomes too time-consuming, hiring another individual to complete the assessments may be beneficial. The assessment portion should not be too arduous or pose a potential injury risk to any of the participants. The onsite assessment tool must have a scoring measure to quantify the outcome.

The assessment tool must be easy to use, straight forward and user-friendly. Any technological component associated with using, setting up, calibrating, and troubleshooting the assessment tool needs to be designed for individuals with little experience in technology and should be accompanied by clear, step-by-step instructions. The input required for the assessment tool should be as minimal as possible. The tool should make direct connections between risky postures and cumulative damage or outcomes.

The total time allocation for the ergonomic program will vary by apprentice level. In level 1 a maximum of 7 hours total can be allocated that can be broken down into different parts. This should include the upfront classroom component, the testing component, and the end of program follow-up testing component. In level 2 and 3, there will not be time to revisit in-classroom information, rather the focus should be on reassessment as a follow-up.

The training program should include information about the purpose of the training program, how the tool works, past data collected from the tool, the importance of technique and long-term benefits. The program should also highlight the value of the training for the apprentices. The program should highlight common attitudes and behaviours that may lead to injury as well as discuss factors that will reduce injury risk. The program should be spread across multiple days instead of all at once. All provided resources must have wording and images that speak to the target audience, and instructors should tailor the messages to the individuals where possible. Instructors should be encouraged to talk about their own experiences with injury and have discussions with the apprentices to share their knowledge. Collaboration with masonry instructors is necessary to ensure appropriate wording is used. In-class instructor materials must provide key talking points, upon which the instructor can personalize or elaborate as they wish. Any included images should be of masons where possible. Both pictures and stick-figures can be used as necessary to convey the desired information. Context should be provided in visuals as much as possible. The materials should be brief but engaging to students. An overall objective is to keep all resources as simple as possible.

6.1.4 List of Deliverables

- Training Program overview
- PowerPoint presentation
    - Ergonomics relevant to masonry
    - Talking points and explanations for instructors
- Pocket Cards
    - Lifting techniques
    - Warm up exercises
- Poster
    - Lifting techniques
    - Warm up exercises
- Onsite assessment tool

- Scoring evaluation

6.2 Training Program

The development of the training program was based on stakeholder interviews, insights from the analysis of expert versus novice working techniques and multidisciplinary knowledge integration from a literature review of best practices and principles for: (i) manual handling training; (ii) motor learning; (iii) adult learning; and (iv) behaviour change models for health promotion. The training program consists of training modules to be completed at level 1, 2 and 3 of masonry apprenticeships. Level 1 will have the most time allocation with both an in-class component to introduce the topic as well as an in-shop component to practice and reinforce the content. At level 2 and level 3, due to time constraints there will only be an in-shop testing component to track progress as well as provide a refresher for the material taught in level 1 and boost awareness. The following tables (Table 15 and 16) outline the integration of principles from the literature into the design of the training program.

Table 15: Integration of Best Practices for Training into Training Program Design

Training Principles	Aspect of program design
Observing workers in working environment	Onsite training tool will provide feedback based on direct observation of workers in working environment. All recommendations are informed from previous research of workers in working environment.
Training tailored to participants	Onsite training tool is based off previous research in masonry and provides targeted feedback for participants. Educational modules and resources are tailored to masonry.
Comparing strategies of expert and novice workers	Previous biomechanical assessments of lifting strategies of novices, apprentices, and experts inform thresholds, recommendations, and coaching cues.
Practice	Practice provided in training sessions with the onsite training tool.
Reinforcement/refresher courses	Reinforcement provided at the end of the skills training course and refreshment of training is provided at each level of the apprenticeship training program (i.e., levels 1, 2 and 3).

Motor learning principles	Integrated into design of onsite training tool (see Table 16).
Behavioural change models for health promotion	Increasing awareness and motivation by providing importance and context of risk information. Providing social support from instructors and targeted messages supporting change. Educating apprentices. Providing resources and detailed information on actions, including training skills and techniques. Targeting all stages in the stages of change model. Providing information about both the threat and behaviour change to factor into appraisals.
Adult learning principles	Explaining the context, process, and reason for training. Providing greater focus on discussion and immediate practical application in educational modules. Objectives of educational modules presented at beginning of content. Making the content relevant and encouraging active participation. Connecting content to previous experiences. Use of actual photos of masons in educational modules and feedback.

Table 16: Integration of Best Practices for Motor Learning into Training Tool Design

Motor Learning Principles	Aspect of program design
Practice	Training sessions provide opportunity for deliberate practice with feedback and coaching cues. Blocked practice of lifting and laying CMUs during construction of standard wall.
Feedback	Augmented feedback from an external source (training tool).
Knowledge of Results	Training tool provides an overall score for the whole body and each joint based on moments and forces.
Knowledge of Performance	Postural feedback and recommendations on technique provided in training tool. Onsite training tool also features a video replay of movement. Spatial feedback about posture and CMU distance provided rather than temporal information.
Feedback Schedule	Built in knowledge of results delay during processing time for the training tool.
Focus of Attention	External focus of attention integrated into coaching cues where possible.
Instruction	Instructions provided based on expert performance.
Understanding the Skill	Educational modules explain the skill prior to practice.
Benchmarks for Objective Evaluation of Learning	Training tool provides joint scores, which can be reviewed over time to objectively evaluate learning.

6.2.1 In-Shop Component

The in-shop component of the training program entails the utilization of the training tool during individual sessions with apprentices. The onsite training tool is designed to help apprentices learn the movement techniques of expert masons. The training tool will be used to assess the apprentices' lifting techniques to provide individual and customized feedback to improve safety. Motion data to be used in the tool will be collected using wearable sensors.

Given the tight constraints on instructors' time, we believe that the in-shop assessments should be conducted by a third party. This will allow each student to be taken aside to conduct an assessment without taking away from the instructors' teaching time. Each student should have the opportunity to complete an individual assessment at the beginning and end of the 8-week skills training course at level 1. At level 2 and 3, this can be limited to only one assessment during the 8-week skills training course. The exact schedule is at the discretion of the instructors i.e., could schedule any number of students per day when the apprentices are practicing skills and are free to step aside from the main course activities. The current tool is designed to be used while building a standard wall. Suggested time per student is around 30 mins, which reflects an ample amount of time to measure a truer representation of technique with fatigue. This will help to ensure that apprentices are not just changing their technique to reflect their best behaviour because they are being measured. However, to get the most benefit from the tool, instructors and the third party should encourage apprentices to work as they naturally would. Resources provided for this aspect of the training program includes the training tool software, the wearable sensor suit and other associated hardware, as well as a troubleshooting guide on how to use the hardware and software.

The scoring system and thresholds developed in Chapter 3, were implemented into the training tool to provide feedback on overall scores of the apprentices based on the motion capture data during the task. The research from Chapter 4 informed the postural thresholds for the tool, as well as the undesirable and desirable movement characteristics.

My role was to design the training tool and feedback and provide direction for the user interface of the tool. Development of the tool was carried out by a previous master's student, Mohsen Diraneyye and a current master's student, Ahmad Mahmassani. The training tool receives inputs from the IMU suit as .BVH files containing the motion data, which is then processed via a MATLAB code to calculate the static and dynamic loads. These loads are then used to generate the joint and whole-body scores based on the equations and scoring system previously reported. The tool also analyses the kinematic data to identify critical points at which the apprentices have exceed suggested thresholds for joint angles where the body is exposed to higher risk. This then triggers the postural recommendations, which are presented in a dashboard that the apprentices can view to improve their lifting technique. A final report of the scores and postural recommendations are generated for the instructors to keep in their records. A mock-up of the user interface design for the risk overview report within the enhanced training tool is presented in Figure 49. Additional mock-ups of the enhanced training tool design are included in Appendix F.

It is important to note here that the use of the term risk here was not supported with epidemiological data, rather this training tool employed simplified language with the intent of communicating directly to trainees. While the scoring system has no direct implication upon injury or MSD risk, the system uses expert behaviour to model acceptable levels of joint loads. Expert lifting behaviour has been shown to correlate with reduced exposures and potentially safer behaviour while lifting.

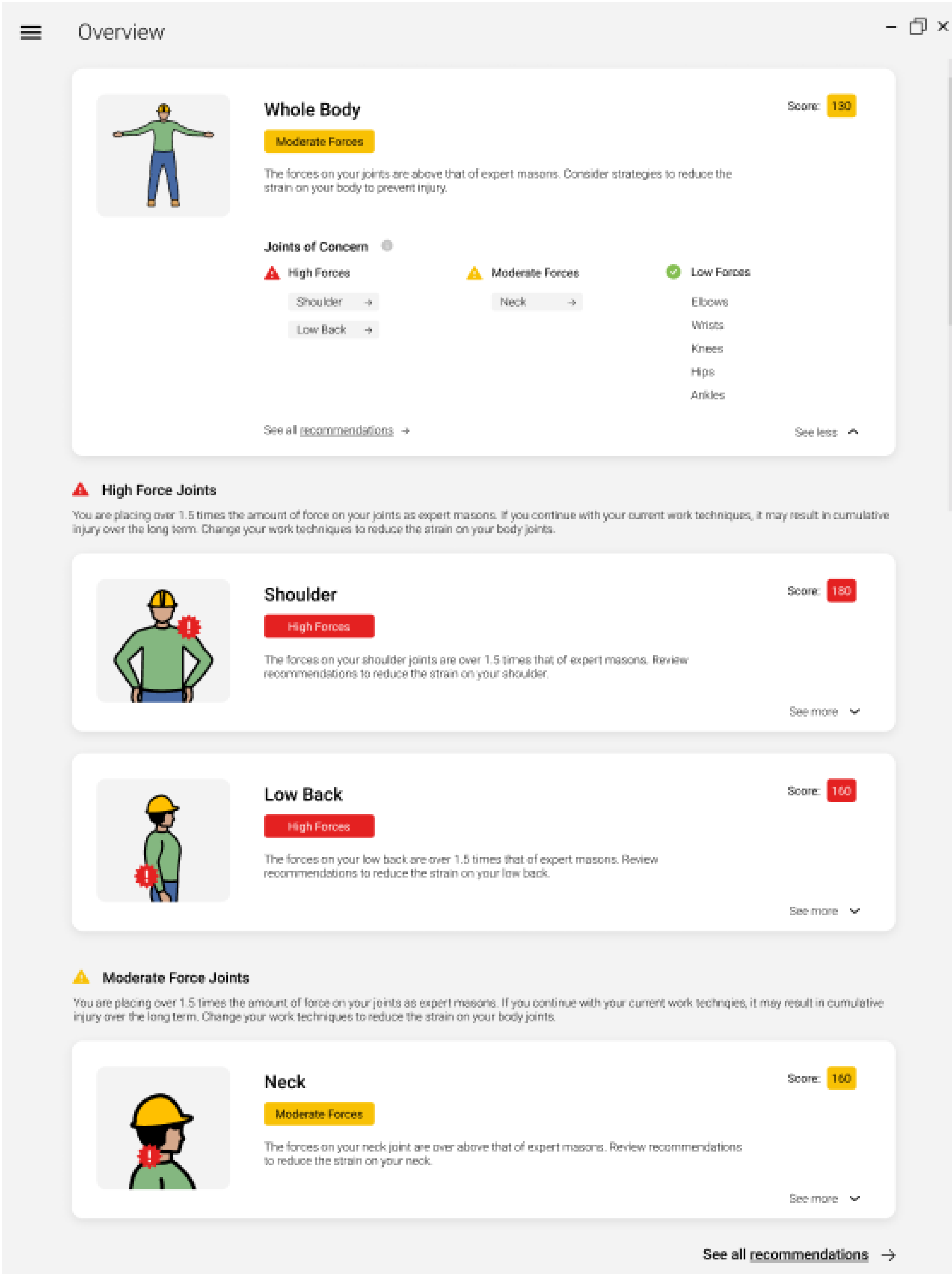


Figure 49: Mock-up of User Interface Within the Enhanced Training Tool

Once the numeric parameters for the tool's feedback criteria were set, the next step was to create the feedback that the apprentices would be given once the criteria were triggered. For each joint threshold, a postural recommendation was provided to improve lifting technique. Each recommendation provides a quick, catchy coaching cue to target the desired behaviour, as well as additional details to further explain the desired lifting motion as well as context for injury risk of the undesired motion. All coaching cues were reviewed with an NSCA-Certified Personal Trainer®. Emphasis was given to external cues as opposed to internal cues where possible, in line with the literature on the benefits of external cues. However, this was not always possible. For example, initially the cue for bending at the hips was "Butt towards the wall!", which focused on providing an external directional cue, under the assumption that the apprentices would be working inside a larger training center and the wall would refer to the training center's walls. However, after a stakeholder interview, it was pointed out that 'the wall' might be confused with the wall that the masonry apprentices were building as part of the trade. If this cue were changed to "Butt away from the [masonry] wall!", this might not always hold true either. For example, when apprentices are picking up blocks, they might position themselves parallel to the masonry wall. This cue was changed to "Stick your butt out!", which has a more internal focus. This demonstrates the complexity of attempting to provide all-encompassing cues for a trade with a lot of variability. In this case, it would be preferable for an instructor to provide a specific external cue with environmental context at the time of feedback, rather than in advance as in these general cues.

To accompany the recommendation, images are presented to visually compare the undesired motion alongside the desired motion. These images were stills of the videos collected during the experimental data collection of both apprentice and expert masons. All faces were blurred to maintain anonymity. The stick figure images generated from the motion data of the k-means cluster posture were used to highlight the joint positioning of the body. For each of the poses identified to represent desired and undesired postures from the k-means clustering postures, frames from the associated video file were scanned to find the representative posture. Where the k-means cluster posture was unclear, or obscured from view in the participants' video, another still from the collection of video files were used to depict the intended posture. Lastly, where it was difficult to view the intended posture in many of the videos, such as angles at the wrist and neck, original photographs were taken to replicate the poses. It was important to feature images of masons with the additional context of their work environment, or images representative of the masonry industry to help the apprentices connect with the images. The following is an example of a coaching cue, and the accompanying image (Figure 50) triggered for an excessive neck flexion posture:

> **KEEP YOUR HARD HAT TOWARDS THE CEILING!**
>
> Holding your neck in a bent position repeatedly over the workday can cause neck pain. Avoid bending your neck in extreme angles to look downwards for too long. Try to keep your neck in line with your spine or only use a slight bend. Some neck flexion is acceptable for short durations, but extreme flexion should be avoided.

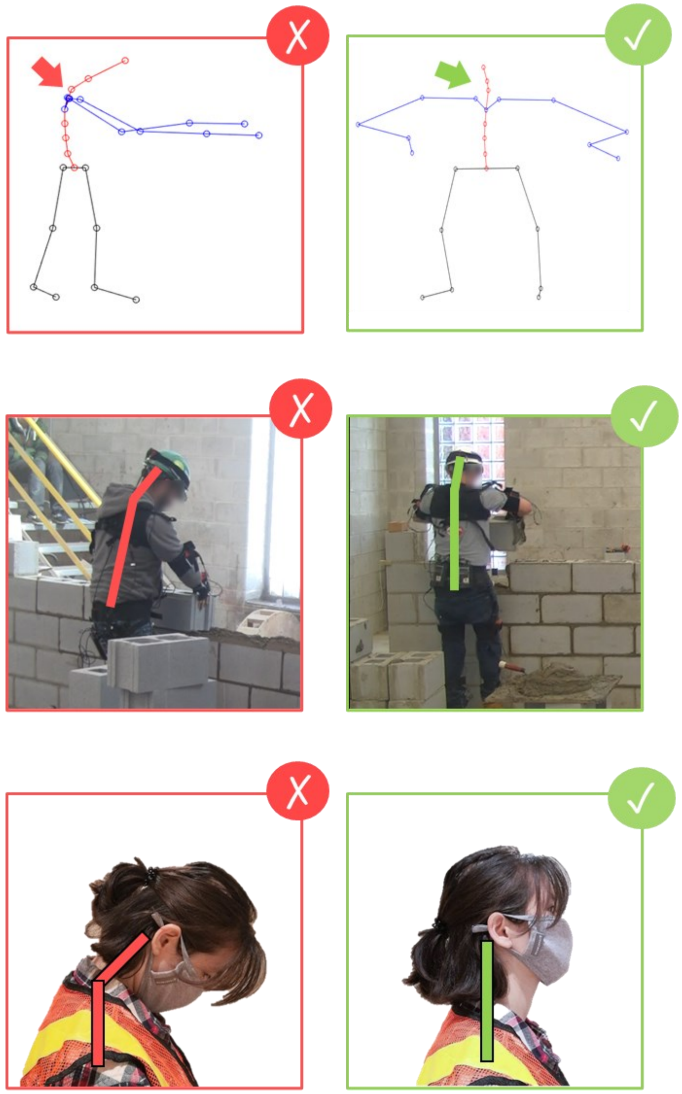


Figure 50: Training Tool Feedback for Neutral Neck Postures

6.2.2 In-Class Component

The in-class component includes educational modules in the form of a PowerPoint presentation, with a focus on initiating discussions among instructors and apprentices. The PowerPoint presentation is supplemented with notes for the instructors in the margins, as well as other educational resources such as posters and pocket cards for the apprentices. The first drafts of the educational resources (PowerPoint, posters, and pocket cards) were reviewed with stakeholders for additional feedback on the deliverables. Changes were made prior to the final versions.

The PowerPoint is not intended to replace the expert judgement of the instructors. It is merely to serve as a bare-bones outline for the courses and to help initiate discussions. The instructors are encouraged to supplement the content with their own experiences and expertise when discussing the topics. The instructors are also encouraged to alter or modify the content of the presentation at their discretion. There are a total of 5 modules: 1) Muscle injuries in masonry; 2) Preventing muscle injury; 3) Warming up before work; 4) Lifting techniques; and 5) Motion-based training tool.

An additional optional module "Learning proper body movements" is hidden in the PowerPoint file following the lifting techniques module as a reference for instructors only. The instructors can unhide this section if they feel it would be benefit for the students. This module provides additional exercises to reinforce proper body movements that should be applied while lifting. Throughout the presentation there are some notes in the margins to guide your discussions and help explain the concepts more clearly. The course is designed to have not only information but to create discussions in class.

The in-class component is designed to be used in the training program with level 1 apprentices only. The in-class component can be broken up into their 5 respective modules, which can be taught on different days so that apprentices do not have to sit through the entire thing in one go. The estimated time is 1-2 hours in class.

The resources provided for the in-class component are as follows:

- PowerPoint Presentation (Appendix G)
    - 5 modules focusing on muscle injuries in masonry, preventing muscle injuries, warming up before work, lifting technique and the training tool.
- Posters (Appendices H and I)
    - Two posters are provided to accompany the in-class material on safe lifting techniques and a warm-up routine. The posters are sized 91.4x61cm (36x24in) and can be printed and hung in any training location as a reminder of the course material.
- Pocket Cards (Appendices H and I)
    - Two pocket cards are provided to accompany the in-class materials and posters on safe lifting techniques and a warm-up routine. Multiple card options are provided: 7.6x12.7cm (3x5in) or 5x9cm. These can be printed and given to the apprentices to keep in their wallets alongside some of the other pocket cards they may have for other safety topics.

6.2.2.1 PowerPoint Presentation

The PowerPoint presentation was developed based on the recommendations from Chapters 2, 4, and 5, including insights from both the literature on ergonomics programs and the user interviews. For example, the PowerPoint content was broken down into separate modules so that the instructors could break it up and teach parts on different days. There was an emphasis on generating discussions and applying the knowledge. All the information included was tailored to the masonry industry as much as possible, for example rather than generic ways to reduce injury risk, specific examples were given with respect to the masonry sector. Visuals were provided as much as possible and text on the slides were reduced. The content avoided technical jargon and was simplified to enhance understanding. Example slides from the PowerPoint presentation are presented in Figures 51 and 52. A copy of the full educational module is accessible available in Appendix G.

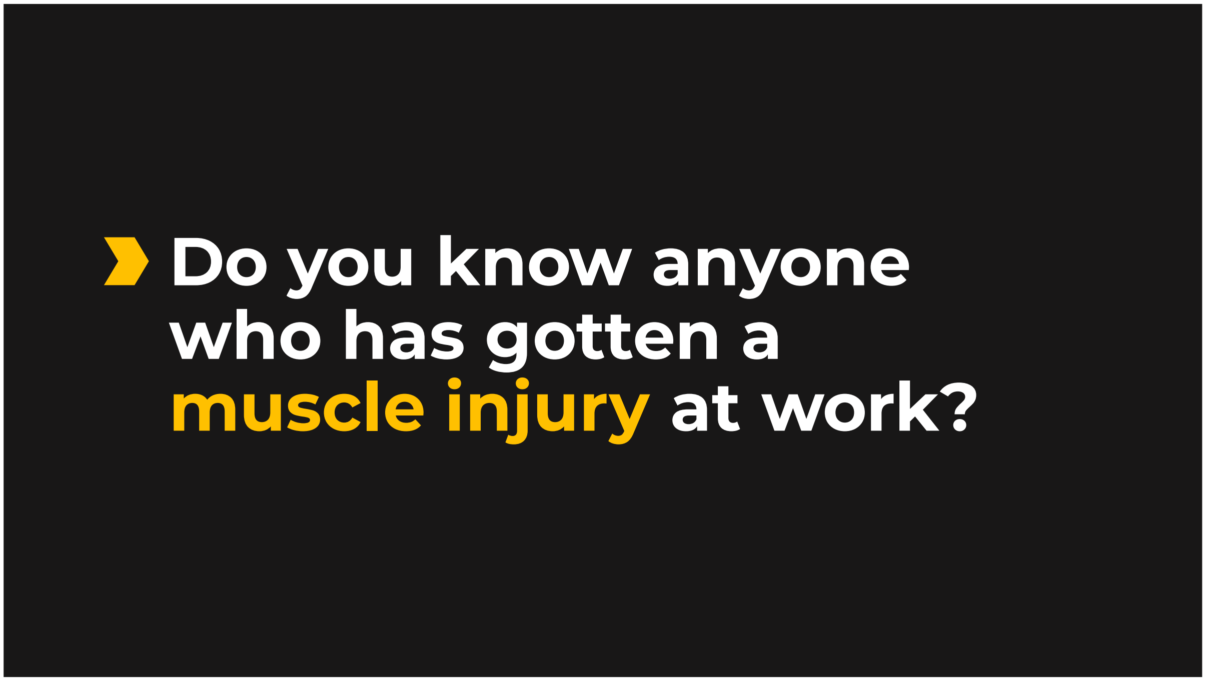


Figure 51: Discussion Prompt from the PowerPoint Presentation

Figure 52: Informative Slide from the PowerPoint Presentation

6.2.2.2 Posters and Pocket Cards

A poster and pocket card were created for best lifting practices and an example warm up routine. For the best lifting practices, the top ten recommendations for desired body postures from the research were identified and the associated coaching cues were used to provide the content for the poster and pocket card. The main illustration used for the lifting poster, Figure 53, was based off a video still of an expert mason from the data collection to further tailor the content and stay true to the masonry context. Simple concise phrases with easy-to-understand language were used to provide additional details about the coaching cues. Only key information was retained on the pocket cards due to the lack of space, Figure 54.

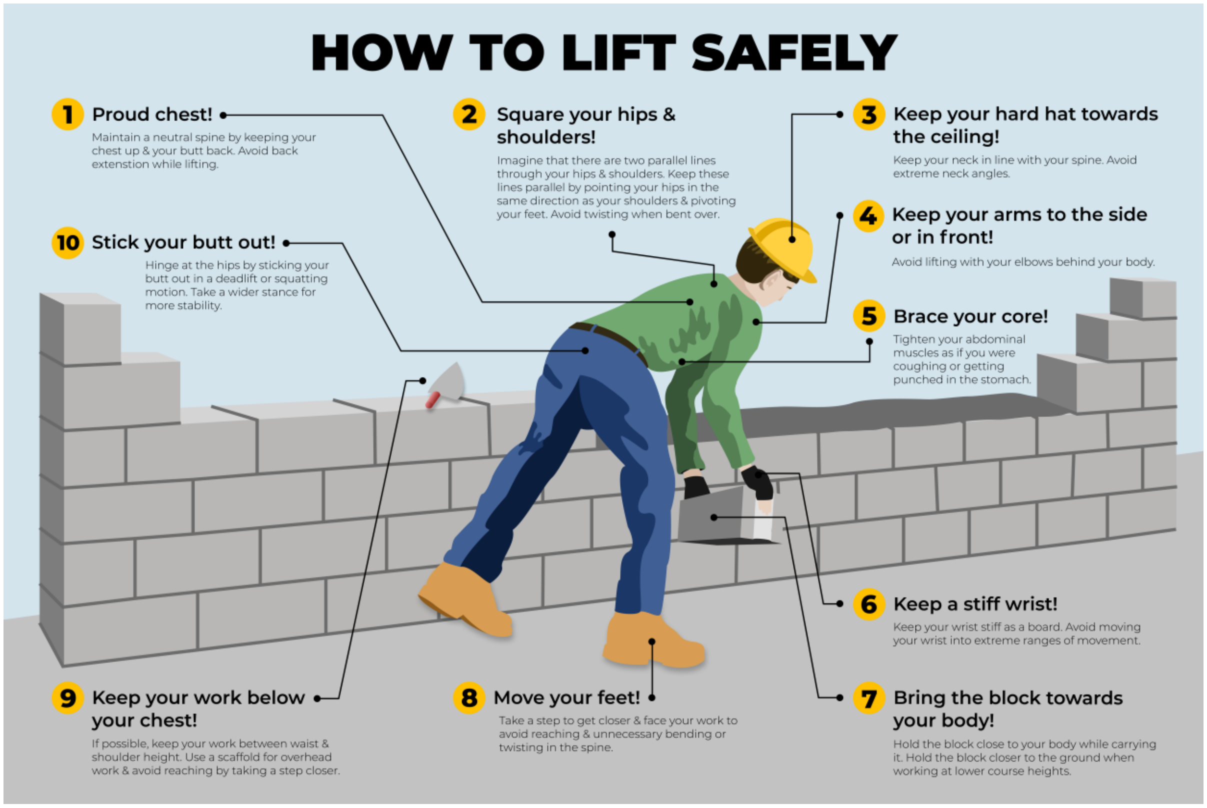


Figure 53: Lifting Poster

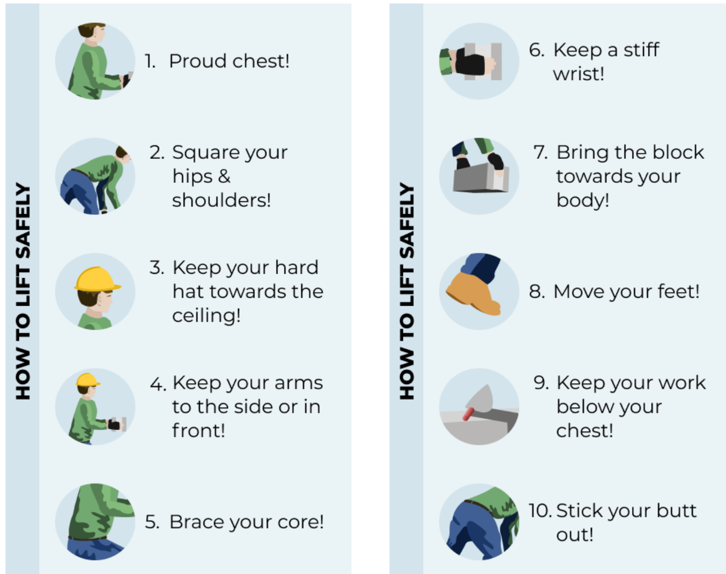


Figure 54: Lifting Pocket Cards

For the warm-up program, a sample routine was created to target the various body parts engaged in masonry work. Other warm-up routines available online, and stretching programs promoted for the construction industry were reviewed. However, many of the resources focused on stretching for construction workers, not warming up and many of the warm-up routines designed for working out at the gym were impractical in a construction context. The warm-up routine was created specifically for masonry workers. The routine was designed to be completed in 5-10 minutes, with a maximum of 10 exercises, practical exercises that did not need any external equipment or supports, focused on compound movements that prepared the individual for manual labor and lifting work. The warm-up routine targeted heart rate, upper body (arms, shoulders, upper back, and low back) and lower body (hip flexors, quadriceps, hamstrings, glutes). The PowerPoint presentation also provide alternate options for those who desired more discretion, did not want to do the traditional warm-up, or did not feel like they had time to warm up before work. The warm-up program was reviewed by an NSCA-Certified Personal Trainer®.

Illustrations were created to accompany the exercise program. For the illustrations, a variety of skin tones and sexes were used to promote inclusivity within masonry workers. To be representative of masonry, all the figures in the illustrations were depicted wearing clothes one might find on the job site such as hard hats, work boots, gloves etc. The same colours and fonts between pocket cards, poster and presentation were used to maintain cohesiveness between the different educational resources. The warm-up poster and pocket cards are presented in Figures 55 and 56. A full copy of all posters and pocket cards for both safe lifting and the warm-up routine are available in Appendices H and I, respectively.

Figure 55: Warm-Up Poster

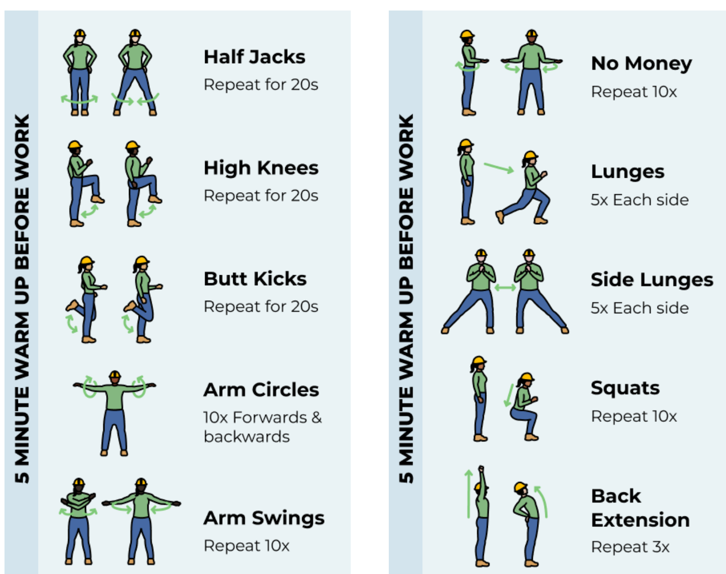


Figure 56: Warm Up Pocket Cards

Chapter 7
Conclusions and Future Work

Masons face high physical demands and thus are more susceptible to MSDs. Onsite assessment of these physical loads is difficult for practitioners and typically results in the use of observational based methods. Furthermore, among tradesmen there is a lack of education and awareness surrounding MSDs. Lifting technique during manual handling tasks has been shown to effect low back compression forces. There is some evidence for training based on expert work strategies to reduce exposure to MSD risks. The goal of this thesis was to design and develop a practical training program to teach apprentices safe lifting techniques and potentially reduce their exposure to MSD risks. Sex-specific thresholds were established to model expert joint loads during 7 representative masonry tasks. The movement techniques of novices, 1st year apprentices, 3rd year apprentices and journeymen were analyzed and compared for a standard wall build to elicit ideal and unideal markers of technique. Integrating knowledge from the literature, these markers of technique were translated into postural thresholds and integrated into the training tool. The recommended techniques were translated into coaching cues and descriptive feedback and implemented into the training tool and other resources for the overall training program. The assessment tool was redesigned to be more user friendly and a component of a larger MSD training program. Lastly, additional educational resources were developed for use in the overall training program. Integrating this training into apprentice skills training classes encourages awareness of MSDs and good lifting techniques early on in masons' careers to reduce MSD risk.

7.1 Contributions to Knowledge

There are several ways in which the research undertaken in this thesis contributes to the existing literature. As noted previously, onsite assessment methods usually comprise of observational methods, or calculated loads without context, which is often difficult for non-practitioners to make sense of. The industry-specific biomechanical based scoring system proposed in this thesis models expert joint loads for a range of masonry tasks. It has the capacity to improve manual handling training by providing quantitative load metrics, deployable as learning indicators for apprentice masons. The effectiveness of the training program can be evaluated through biomechanical markers of risk, following further validation of the scoring system. The assessment tool can also be used to provide insight into relative joint loads associated with job and workstation design and could be leveraged to improve workplace ergonomics, where possible, in addition to training. The methodology used to develop the thresholds and scoring system can be applied to other construction trades and manual handling tasks in other industries.

This thesis also compares and analyses the differences between the postures and movement techniques of expert and apprentice masonry workers. Previous literature has compared the forces and moments between these worker groups, but none has compared their kinematics. Similarly, while studies have compared expert and novice workers on lifting tasks, few compare manual handling tasks within the context of a construction trade such as masonry. The kinematic analysis of expert and apprentice techniques have also been implemented into a novel training tool and program designed for apprentice masons. This training tool provides recommendations on lifting technique to reduce MSDs in apprentices. Furthermore, a comprehensive training program was designed by incorporating user interviews, findings from masonry research and best practices from the literature. Again, this methodology can be applied to training for other masonry tasks and construction trades.

The last contribution of this thesis is the knowledge translation and dissemination to the masonry sector. The outputs of the training program and resources such as the training tool, the in-class educational modules, the posters and pocket cards were shared directly with masonry organizations in Ontario, so that it could be implemented into Ontario masonry training schools. The resources are designed to be easy to understand and as user-friendly as possible, such that the findings from our research could be shared with masons to raise awareness, increase knowledge, and ultimately, reduce MSD risk.

7.2 Limitations

This research has several limitations. The postural analysis was focused on the standard wall build as a representative lifting task for 1st year apprentices, but it did not cover other difficult tasks masons may have to engage in. Therefore, the training tool recommendations are limited. Additionally, the quantification of the postural analysis into joint angle thresholds does not fully capture the full scope of the techniques used by the experts nor their implicit knowledge. Regarding the establishment of joint force and moment thresholds, the sample size of experts was small and there was a lack of female mason representation in the data collection, resulting in a reliance on ratios from the literature to establish threshold values. Furthermore, the proposed scoring system lacks epidemiological data to allow a connection to injury risk. The static model using in this thesis may have underestimated joint loads. This thesis uses joint reaction forces and moments as a marker for risk; however, the impact of muscle loads and co-contraction with respect to MSD risk are not considered. Lastly, ergonomic interventions that rely on changing worker behaviour is limited in its ability to prevent MSDs. Training programs should be implemented alongside other measures to reduce MSDs.

7.3 Recommendations

Future research needs to investigate the validity of the scoring system for the assessment of MSD risk, and further refine the scoring system. Future research should also investigate the usability and training efficacy of the program and tool, as well as the user experience of the apprentices and instructors. Additionally, demonstrating financial and productivity gains through cost-benefit and return-on-investment analyses would be a greater driver for adoption in masonry and the adoption of similar programs in other construction trades. Future work on the training program and tool should consider implementing some of the suggestions and desires outlined by the masonry instructors in the user interviews, such as instantaneous feedback, improved wearability of the motion capture suits, developing apps to manage the training tool and incorporating augmented or virtual reality in training.

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Appendix A
Summary of Literature on Manual Materials Handling and Lift Training Studies

Table 17: Description of MMH and Lift Training Study Methods and Training Type

Study	Participants	No and Duration of Sessions	Length of study/ Follow-up	Description of Training	Outcome Measures
Agruss et al. 2004	Intervention (EMG) = 10 Intervention (Verbal acceleration index) = 9 Controls = 9 Students	2×Estimated 1.5 hours	3 weeks	Feedback sessions (2) on lifting task – EMG feedback or verbal acceleration index	Lumbar compression
Best 1997	Intervention = 18 Comparison 1 (“Control”) = 19 Comparison 2 = 18 Nurses	32 hours (in total)	12 months	Semi squat posture and weight transfer techniques such as bracing, pivoting, lunging, and counterbalancing load	Self-reported back pain Observation of handling technique
Boocock et al. 2019	Intervention = 18 Comparison = 16 University population	1×20 min	1 session	Real time lumbosacral postural feedback when flexion exceeded 80% of maximum flexion from standing	3D kinematics and kinetics Rating of perceived exertion (RPE)
Brown et al. 2002	Intervention = 30 Warehouse workers 79 participants from assembly department monitored	Unclear	12 months	Information on management of back pain Awareness for lifting and handling, risk assessment Fast-track physiotherapy	Self-reported musculoskeletal discomfort Sickness absence
Carlton 1987	Intervention = 14 Control = 16 Food services employees	1×1 hour	3 weeks	Body mechanics course with individual video feedback	Evaluation of body mechanics (performance; WEST 2 Body Mechanics Evaluation and Work Capacity Evaluation Device and Work-Related Body Mechanics Evaluation)
Chaffin et al. 1986	Intervention = 26	1×4 hours	7-9 weeks	Instruction emphasizing lifting technique	Videotape of workers’ postures (performance)
Daltroy et al. 1997	Intervention = 1703 Control = 1894 US postal workers	2×1.5 hours	5.5 years	Education program – back safety, proper lifting and handling techniques, yearly reinforcement training	Back injury rate

Dehlin 1981	N = 45 Exercise, education and control groups Nurses	8×45 min	8 weeks	Conditioning exercises or education (lifting advice; short lever arms and lifting together)	Self-reported low back pain, psychological perception of work and physical work capacity
Donchin et al. 1990	Back school = 46 Calisthenics = 46 Control = 50 Hospital employees	Back school: 5×90 min Calisthenics: Biweekly × 45 min (for 3 months)	1 year	Back school: instruction on body mechanics and exercises Calisthenics: flexion and pelvic tilt exercises	Physical capacity and episodes of low back pain in the last month
Doss et al. 2018	Intervention = 10\Female nursing students	1 session Duration not reported	Single session	8 repetitions of 3 different tasks while a certified personal trainer and ergonomics student provided verbal feedback on posture and lifting mechanics Real-time audible feedback with respect to trunk flexion	Trunk kinematics, task completion time
Fanello 2002	Intervention = 136 Control = 136 Nurses and cleaners	6 (length unclear)	2 years	Theoretical lift training and advice during work	Self-reported back pain
Feldstein 1993	N = 55 Nurses	1×2+8 hours	1 month	Training on lifting and technique for patient transfer	Self-reported back pain and fatigue BIPP Transfer evaluation
Gagnon 2003	Intervention = 10 College students with 3-12 months occupational manual handling experience	1 session Duration unclear	Unclear	Education on biomechanical principles Video on expert versus novice manual handling strategies and verbal feedback sessions	3D kinematic data, net low back moments and asymmetrical moment and mechanical work on load
Gross 1984	Intervention = 11	Unclear	Unclear	Surface EMG of erector spinae muscles with biofeedback	Muscle activity (Spinal stress)
Hartvigsen 2005	N = baseline (follow-up) N = 345 (255) Intervention = 184 (140) Control =161 (115) Nurses	104×1 hour + 4×2 hours	2 years	Education according to the 'Bobath principle' (lifting principles) and use of low-tech ergonomics interventions (plastic sheets and slings) Control group had 1×3 hour session on lifting technique	Self-reported episodes of low back pain and number of days with low back pain in the past year

Hellsing et al. 1993	Intervention = 19 Control = 33 Student nurses	~2 hours per week over 2 years	1 year	Theoretical and practical training on ergonomics, behaviour and patient handling	Observation of work movements (correct vs. incorrect lifts), self-reported MSD symptoms and knowledge
Hodder et al. 2010	Intervention = 12 Female novices	1×2 hours	1 day	2 hours of standardized instruction on Back Injury Prevention Program (BIPP), lifting principles and practice with feedback on technique	Muscle activity of back muscles measured bilaterally (trapezius, external oblique, erector spinae, and posterior deltoid or rectus femoris depending on task), maximum angular displacements and range of motion (ROM) of the thoracolumbar spine in the sagittal, lateral and twisting directions
Jaromi et al. 2012	Intervention = 62 Control = 62 Nurses	6×50 min	12 months	Education, active therapy, stretching and exercises and ergonomics Control group received passive physiotherapy for same amount of time as training for the intervention group	Body posture and self-reported pain intensity
Jensen et al. 2006	210 Technique training = 53 Stress management = 49 Control = 61 Homecare workers, nurses and nurse's aides	Technique training: 2×4 hours of classroom training + workplace training Up to 30 hours total Stress management training: 10×2 hours	2 years	Instruction on handling technique in classroom and at the work site	Intra-individual change in low back pain in the past 3 and 12 months
Johnsson et al. 2002	Traditional group = 30 Quality circles = 21 Nurses, occupational therapists and physiotherapists	Traditional groups: 4 day course Quality circles: 8× half a day	6 months	Theoretical and practical instruction with a focus on work technique, musculoskeletal problems, job strain and the patients' experience	Work technique based on 7 criteria and self-reported physical exertion, job strain and musculoskeletal problems
Kraus 2002	N = 12772 Back belts, lifting advice and control group Home care workers	Unclear	28 months	Back belt Lifting advice (safety practices when handling patients)	Low back injury rates per 100 full time equivalents

Lavender 2000	Intervention = 293 Warehouse workers	5×30 min	Unclear	Lifting with biofeedback and coaching	Percent change in forward bending moment, twisting moment and side bending moment
Lavender et al. 2002	Intervention = 265 Grocery distribution employees	1×30 min	Unclear	Lifting with biofeedback and coaching	Percent change in forward bending moment, twisting moment and side bending moment Classification of lifting style
Lavender et al. 2007	Intervention = 891 Control (video) = 944 Distribution center employees	5×30 min	12 months	Lifting with LiftTrainer™ which provided biofeedback based on instantaneous spine moment magnitude. Sessions conducted 1-on-1 with a coach for up to 5 sessions (average of 3.5 sessions) Control group viewed a video on lifting techniques once	Injury rates, turnover rates, kinetic data (L5/S1 moments)
Müller 2001	N = 51 nurses Trained group and control group	Unclear	12 months	Coordination training in space curl, kinaesthetics and pack protective patient transfer	Back pain frequency and quality of life
Nygård et al. 1998	Intervention = 21 Production line workers	1-3×1.5 hours	2 weeks	Theoretical and practical lift training using the critical mental system method Videotaping used for feedback	Working postures (OWAS method) and rating of perceived exertion
Poosanthanasarn et al. 2005	Intervention = 35 Controls = 17 Thai auto parts factory workers	5 sessions for workers and head workers 2 sessions for head workers, managers and safety officers Duration unclear	3 months	Management support, workstation and manual handling equipment, training in work posture, health education and warm up work exercises	Muscle activity of left and right erector spinae and multifidus muscles (EMG)

Reddell 1992	N = 642 Back belt = 57 Training = 122 Belt and training = 57 Control = 248 Belt with discontinued use = 88 Belt and training with discontinued use of belt = 70 Airline baggage handlers	1×1 hour	8 months	Training video and hands-on instruction (Balancing load, pivoting instead of twisting, getting close to load, squat lift, squaring load, maintaining three point contact), back belt and combination of the two	Back injury rate, lost workday case injury incident rate, restricted workday case injury incident rate, lost workdays and restricted workdays rate, and worker's compensation rate
Resnick and Sanchez 2009	Classroom emergency = 4 Classroom non-emergency = 4 Contextual emergency = 4 Contextual non-emergency = 4 Nurses	Unclear 30 min of practice following main training session	1 week	Classroom: trained in a classroom environment with subsequent practice time Contextual: practice patient handling in scenarios with subsequent practice time Emergency: practice sessions conducted under time pressure or created stress Non-emergency: absence of time pressure	Torso postures and compliance with trained techniques
Schenk et al. 1996	Back school = 74 Video = 64 Control = 67 Local industry workers	Back school: unclear (estimated equal time as video group) Video: 1×2 hours	Unclear	Back school: cognitive learning and lifting practice Video: instruction on manual handling technique, education on anatomy and biomechanics	Lumbar lordosis during lifting, knowledge
Scholey 1983	Intervention = 4 Nurses	Unclear Estimated 1 training session	3 weeks	Practical patient handling training and feedback on back stresses	Back stress as indicated by mean peaks of intra-abdominal pressure
St. Vincent et al. 1989	Intervention = 32 Orderlies	12 hours	Between 12-24 months	Theoretical and practical patient handling techniques focusing on 6 major principles	Extent to which the taught handling techniques were used
Stubbs et al. 1983	Intervention = 2 Nurses	4 sessions Unclear duration	15 weeks	Practical patient handling training	Intra-abdominal pressure, posture and technique

Troup and Rauhala 1987	Intervention = 106 Control = 93 Student nurses	40 hours over 5 semesters	5 semesters	Theoretical and practical training on patient handling Video and self-evaluation and practice teaching	Lifting technique by subjective rating
Van Poppel 1998	N = baseline (1 year follow-up) N = 312 randomised (268) Lumbar support and education = 70 (59) Education = 82 (73) Lumbar support = 83 (66) Control = 77 (70) Cargo handlers	3×1.5-2 hours	6 months	Education (anatomy and lifting techniques), lumbar support and combination of the two	Low back pain incidence Sick leave
Videman et al. 1989	N = skill assesses Intervention = 106 Control = 93 Nursing students	40h over 2.5 years	3 years	Practical and theoretical training	Self-reported back pain, rate of back injuries and observation of handling technique (performance)
Warming et al. 2008	Education = 55 Education and fitness = 50 Control = 76 Nurses	Education: 4 day course Fitness: 16×1 hour	12 months	Education on lifting technique alone and in combination with physical fitness training	Self-reported perceived low back pain, pain level, disability and sick leave and knowledge
Wood 1986	Unclear Intervention and Control group Nurses	Unclear	1 year	Feedback on correct technique	Wage-loss claims for back injuries based on patient handling
Yassi 2001	N = baseline (1 year follow-up) N = 346 (261) Safe lifting = 116 (85) No strenuous lifting = 127 (94) Control = 103 (82) Nurses	1×3 hours	1 year	Safe lifting, no strenuous lifting and control group Handling techniques and use of available equipment	Self-reported back pain and fatigue Injury rates

*Table made with reference to the original studies and Clemes et al. 2010, Martimo et al. 2007, Hogan et al. 2014
Significantly increased/greater ▲ or decreased/lower ▼
Non-significantly increased/greater △ or decrease/lower ▽
No sig. difference = no significant difference
ROM = range of motion

Table 18: Results of MMH and Lift Training on Kinetics and Muscular Activity and Kinematics and Technique

Study	Kinetics and muscular activity	Study	Kinematics and technique
Agruss et al. 2004	16.7% ▼ low back compression in EMG feedback group	Best 1997	No sig. difference on handling technique
	25.3% ▼ low back compression in the verbal acceleration group	Boocock et al. 2019	▼ lumbosacral flexion in training group over 20 mins compared to non-training group
	11.2% ▼ low back compression in control group		▲ rate of lumbosacral flexion and angular velocities over time in non-training group
	Verbal acceleration intervention ▼low back compression compared to control group		▲ peak percentage trunk flexion and rate of flexion over time in non-training group
	Changes persisted after a 7-day interval without training		▲ peak hip and knee joint angular velocities in training group
	No sig. differences in reduction of low back compression of the EMG feedback group compared to the control group		No sig. difference in peak knee flexion at start of task (knee flexion reduced in non-training group over time, while training group maintained similar knee flexion) or mean peak hip flexion
Boocock et al. 2019	▲ lumbosacral passive resistance moment and greater rate of increase over time in non-training group	Carlton 1987	▲ performance on novel task for intervention group
	No sig. differences in peak back, hip or knee moments		No sig. difference in performance in working environment
Gagnon 2003	▼ mechanical work on load and net low back moment at deposit for trained task and analogous lifting task	Chaffin et al. 1986	▲ Improvement 2/5 criteria for subjective evaluation of lift performance
	No sig. difference for net low back moment at takeoff or asymmetrical moments	Donchin et al. 1990	▲ trunk forward flexion for the calisthenics group compared to before and compared to the other groups
Gross 1984	▼ in muscle activity for 45% of trials with biofeedback compared to no biofeedback	Doss et al. 2018	▼peak trunk flexion and trunk rotation to the left and right for bed to chair task
Hodder et al. 2010	▼ left trapezius activity and ▽ all muscles but greatest for right posterior deltoid activity for patient repositioning from the side of the bed		▼peak trunk lateral bend to the left for the sling task
	▼right trapezius, right posterior deltoid, left erector spinae, and left external oblique for patient repositioning from the head of the bed		▼ peak trunk flexion/extension, lateral bend and rotation velocities and accelerations for bed to chair task
	▼ peak left trapezius and ▲ peak right rectus femoris for the bed to wheelchair patient transfer	Feldstein 1993	▲ BIPP scores for quality of patient transfer in intervention group (19%)
Lavender 2000	▽ side bending and twisting moments (no statistical tests performed)	Hellsing et al. 1993	△ number of correct lifts of intervention group compared to control
Lavender et al. 2002	▼ in forward bending, twisting and side bending moments with training	Hodder et al. 2010	▲back extension and ▼ ROM in the sagittal plane for patient repositioning from the side of the bed
	Magnitude of moment reduction dependent on lifting style adopted		▼ peak right bend and lateral range, and ▲ peak left twist for patient repositioning from the head of the bed

Lavender et al. 2007	▼ rate of low back disorder for those with a low mean twisting moment (< 30 Nm) at the end of the first session compared to the controls		No significant difference in trunk postures for the bed to wheelchair patient transfer
	▽ flexion, side bending and twisting moments over course within training sessions	Jaromi et al. 2012	▲ improvements in posture for intervention group than control group
Poosanthanasarn et al. 2005	▼ in muscular low back muscular activity of intervention group	Johnsson et al. 2002	▲ performance on 6/7 criteria for work technique after training for both learning models
	No sig. differences in muscular activity of control group	Nygård et al. 1998	▲ Bending on legs and ▼ standing on only one leg
			No sig. difference in back postures
Scholey 1983	▼ back stress after training	Resnick and Sanchez 2009	▼ torso flexion and rotation and use of safe practices after training
			▼ torso flexion and rotation, and use of safe practices for contextual training group compared to classroom
			No sig. difference for torso flexion and rotation or use of safe practices between the emergency and non-emergency groups
		Schenk et al. 1996	▲ maintenance of lumbar lordosis during lifting in back school group compared to other groups
		St. Vincent et al. 1989	Infrequent use of handling techniques as taught in training
			Training used more frequently for vertical handling operations compared to horizontal handling operations
		Troup and Rauhala 1987	▲ technique of trained group compared to control
			Technique of the trained group rated poor to good (between 1-2 out of 3)
		Videman et al. 1989	▲ performance of intervention group compared to control

Significantly increased/greater ▲ or decreased/lower ▼
Non-significantly increased/greater △ or decrease/lower ▽
No sig. difference = no significant difference

Table 19: Results of MMH and Lift Training on Injury Rates and Sick Leave and Days of Work

Study	Injury Rates and Other Rates	Study	Sick leave and days off work
Daltroy et al. 1997	No sig. difference in injury rate, cost/injury and rate of repeated injury after return to work	Brown et al. 2002	56% reduction in sickness absence from 87 to 38 days
Kraus 2002	Marginally ▼ low back injury rate in back belt group No sig. difference in low back injury rate in lifting advice group No sig. difference in back injury rate in lifting advice group compared to back belt group at long term follow-up	Daltroy et al. 1997 Reddell 1992	No sig. difference in time off work/injury No sig. difference on lost workdays and restricted workdays rate Marginal ▲ lost workday case injury rate for those who wore the belt then discontinued its use
Lavender et al. 2007	No sig. differences in injury rates or turnover rates	Van Poppel 1998	No sig. difference on incidence or sick leave
Reddell 1992	No sig. difference on back injury rates, restricted workday case injury incident rate and worker's compensation rate for all intervention groups		
Videman et al. 1989	△ Rate of back injuries for controls compared to intervention group during first year of nursing school		
Warming et al. 2008	No sig. difference for disability and sick leave of intervention groups compared to control group at follow-up		
Wood 1986	▽ wage loss claims for intervention group compared to control		
Yassi 2001	No sig. difference for injury rates		

Significantly increased/greater ▲ or decreased/lower ▼
Non-significantly increased/greater △ or decrease/lower ▽
No sig. difference = no significant difference

Table 20: Results of MMH and Lift Training on Low Back Pain and Fatigue and Other Factors

Study	Low back pain/discomfort and fatigue	Study	Other
Best 1997	▽ Incidence of back pain in intervention group (43.8-55.6%)	Best 1997	94% respondents felt training helped
	△ Incidence of back pain in comparison groups (55.6-81.8%)	Boocock et al. 2019	▲ mean RPE in non-training group at the 20-minute mark
Brown et al. 2002	Decrease in musculoskeletal discomfort	Daltroy et al. 1997	▲ knowledge
Dehlin 1981	No sig. differences in back pain	Dehlin 1981	No sig. differences in psychological perception of work
Donchin et al. 1990	▼ episodes of months with low back pain compared to the other groups		Exercise group improved psychological perception in 2/7 variables, and improved physical capacity compared to control group
Fanello 2002	▲ remission in LBP in intervention group	Donchin et al. 1990	▲ abdominal muscle strength for the calisthenics group compared to before and compared to the other groups
	▲longer duration of LBP in control group after 2 years		No sig. difference in isometric strength and endurance of back muscles between groups at follow-up
Feldstein 1993	▽ composite pain and fatigue scores for the intervention group	Doss et al. 2018	▼task completion time for patient transfer from bed to chair by 23.3% (6.2 s)
Hartvigsen 2005	No sig. differences for episodes of low back pain and number of days with low back pain in the past year	Hellsing et al. 1993	▲ knowledge in intervention group
Hellsing et al. 1993	No. sig. differences in MSD symptoms between groups at follow-up	Johnsson et al. 2002	▼ perceived exertion when moving a patient from bed to chair at follow-up after training (all participants)
Jaromi et al. 2012	▼ in back pain intensity for both groups after treatment		92% of participants reported they mostly or always used the technique taught in the training program on 6-month follow-up
	▲ improvements in back pain intensity for intervention group than control group at 6 month and 1-year follow-up		No sig. differences for rating of perceived exertion for other tasks or job strain after training
Jensen et al. 2006	No sig. difference in low back pain for any intervention group	Lavender et al. 2002	No sig. difference in task duration
Johnsson et al. 2002	No sig. differences for musculoskeletal problems	Müller 2001	▲ quality of life in trained group
Müller 2001	▼ back pain frequency in trained group		No sig. difference in quality of life in control group
	No sig. difference in back pain frequency in control group	Nygård et al. 1998	No sig. difference in back postures or rating of perceived exertion
Van Poppel 1998	No sig. difference on low back pain incidence	Schenk et al. 1996	▲knowledge of correct lifting technique and body mechanics of back school group compared to other groups
Videman et al. 1989	△ Incidence of back pain for controls compared to intervention group during first year of nursing school		No sig. differences between the video and control group
	△ cumulative incidence of back pain for both groups during the first year of nursing school	Stubbs et al. 1983	Little improvement in intra-abdominal pressure
Warming et al. 2008	No sig. difference for perceived low back pain and pain level of intervention groups compared to control group at follow-up	Warming et al. 2008	No sig. difference for knowledge of intervention groups compared to control group at follow-up

Yassi 2001	▼ frequency of low back and shoulder pain for safe lifting group		▲ in disability score for education and fitness group compared to the education only group
	▼self-reported fatigue for both intervention groups	Yassi 2001	▼frequency of manual handling tasks for no strenuous lifting group

Significantly increased/greater ▲ or decreased/lower ▼
Non-significantly increased/greater △ or decrease/lower ▽
No sig. difference = no significant difference

Appendix B
Summary of Literature on Novice Versus Experienced Worker Techniques in Manual Handling

Table 21: Biomechanical Analysis of Novice versus Experienced Worker Manual Handling Strategies: Study and Task Description

Study	Inexperienced Workers	Experienced Workers	Participants	Task	Task Description	Methods
Granata et al. 1999	– N = 7 novices – College students	– N = 5 experienced workers – Warehouse workers at a distribution center – Years of experience not reported	N = 12 – No prior history of low back disorders	Box handling	– Lift 13.6 and 27.3 kg boxes at different trunk velocities (preferred velocity, faster than preferred) and asymmetry conditions (sagittally symmetric or 60° to the right) from knee height to an upright posture – 1 min rest between exertions to minimize fatigue	– Surface EMG measured activity of the right and left erector spinae, rectus abdomini, latissimus dorsi, external and internal abdominal obliques – Muscle activity was normalized to maximum voluntary contraction exertions during static flexion, extension, twisting and lateral exertions from an upright posture – Trunk motion recorded from an electrogoniometer – Force plate on ground – EMG assisted biomechanical model used to compute dynamic loads on the spine

Hodder et al. 2010	N = 12 novices – Untrained females without previous patient handling experience	N = 12 Experienced nurses – Previously trained in Back Injury Prevention Program (BIPP) transfers – Average of 11.3 (9.5) years of employment	N = 22 – Ages different: experienced nurses had a mean age of 41.6 (±10.6), while novices had a mean age of 23.7 (±1.4)	Patient Handling	– 3 patient handling tasks: o Patient reposition from side of the bed o Patient reposition from head of the bed o Patient transfer from bed to wheelchair – Patient weight = 81 kg, height = 175 cm	– Surface EMG of the left and right trapezius, external oblique, erector spinae and posterior deltoid or rectus femoris depending on task – Maximal voluntary excitations (MVE) recorded prior to experimental protocol – Peak EMG normalized to MVE for each participant – Lumbar motion monitor measured angular displacements of the thoracolumbar spine in 3D to provide maximum angular displacement and range of motion in each direction
Lee and Nussbaum 2012	N = 6 novices – 5M, 1F – Students with no experienced in frequent lifting tasks	N = 6 experienced workers – 5M, 1F – Workers at local warehouses, construction sites and farms – ≥ 3 years of experience in frequent lifting tasks (lifting/lowering 10/h per week)	– No current or prior MSDs – Novice group was age-matched (± 1 year) with the experienced group – No significant differences between groups for age, anthropometry or isokinetic lumbar extensor strength	Box handling	– 20 lifts and lowers of a box weighing 10% of body mass – Lifting frequency of 10 lifts/min – Symmetric vs. asymmetric lifts o Sagittally symmetric task (0°) with origin and destination anterior in mid-sagittal plane o Asymmetric task had destination 60° to the right – Horizontal distance was self-selected and kept constant – Vertical location of the box at the origin and destination was adjusted so the top of the box was aligned at the participants' knee and elbow joints	– Isokinetic lumbar flexor/extensor strength evaluated with MVCs (dynamometer) – Passive motion capture system – Force plates on ground

Lee and Nussbaum 2013	– Same as Lee and Nussbaum 2012	– Same as Lee and Nussbaum 2012	– Same as Lee and Nussbaum 2012	Box handling	– Same as Lee and Nussbaum 2012	– Same as Lee and Nussbaum 2012 – Torso movement stability determined by the largest Lyapunov exponents of torso flexion/extension angle time series
Lee et al. 2014a	N = 6 novices – 5M, 1F – Students with no experienced in frequent lifting tasks	N = 6 experienced workers – 5M, 1F – Workers at local warehouses, construction sites and farms – ≥ 2.5 years of experience in frequent lifting tasks (lifting/lowering 10/h per week)	– No current or prior MSDs – Novice group was age-matched (± 2 year) with the experienced group – No significant differences between groups for age, anthropometry or isokinetic lumbar extensor strength	Box handling	– 185 lift/lower cycles at a frequency of 15 lifts/min – Procedure based on pilot work to induce moderate-high levels of localized muscle fatigue of the low back and upper arms – Wooden box weighing 15% of body mass (33 x 59 x 24 cm) with handles 21 cm from the bottom of the box – Destination of lift was 60° to the right – Initial horizontal distance of the feet to the lifting origin and destination (38 and 69cm) were constant for all participants – Vertical location of the box at the origin and destination was adjusted so the top of the box was aligned at the participants' knee and elbow joints	– Isokinetic lumbar flexor/extensor strength evaluated with MVCs (dynamometer) – Passive motion capture system – Force plate on ground – Torso movement stability determined by the largest Lyapunov exponents of torso flexion/extension angle time series
Lee et al. 2014b	– N = 8 novices – 6M, 2F – Students with no experience in push/pull tasks	– N = 8 experienced workers – 6M, 2F – Workers currently in jobs required pushing/pulling for 10h/week – 1.5 years of experience	– No current MSDs – Novice group was age matched (± 2 years) with the experienced group – No significant differences between groups for age, stature, body mass, or lumbar isokinetic strength	Cart pushing and pulling	– Cart weighed 250% of body mass, handles at elbow height and preferred height – 3 trials of both push and pull of the cart ~2 m at 2 handle heights (elbow or preferred) at preferred working speeds	– Isokinetic lumbar flexor/extensor strength evaluated with MVCs (dynamometer) – Passive motion capture system – Force plate on ground – Load cells to measure hand forces on cart

Marras et al. 2006	N = 12 Novices – No manual handling experience	N = 12 Experienced workers – ≥ 1 year manual handling experience	N = 24 (3 F, 21 M) – No prior history of low back pain	Box handling	– Repetitive asymmetric lifts at one of 3 possible loads and 6 different frequency levels (2, 4, 6, 8,10 and 12 lifts/min) during an 8 hour exposure period – Testing of each frequency level occurred during 6 separate 8 hour sessions – Initial static load moment was either 8, 36 or 85 Nm, to achieve this, participants were positioned on a force plate relative to the position origin of 3 different loads (1.1, 4.9 or 11.7 kg) – The 8 hour session was separated into 2 hour lifting periods interspersed with two 15 minute breaks and one 30 minute lunch break	– EMG-assisted biomechanical model – Surface EMG activity of both right and left erector spinae, latissimus dorsi, external oblique, internal oblique and rectus abdominus – Trunk kinematics measured using a tri-axial goniometer – Force plate on ground – Spinal loading normalized to the subject's body weight
Riley et al. 2015	N = 12 novices – 6 F, 6M – Excluded if fit criteria of experienced lifters – Excluded if worked in a lifting job that required ≥ 4 hours of lifting/week for > 3 months	N = 11 experienced – 3 F, 8 M – Lifted weights ≥ 3 times/week for the last year or more – Lifting weights included most types of free weight lifting activities (e.g. dead lifts, squats, military presses, bent-over rows etc.)	N = 23 – No health conditions or previous low back pain – No sig. difference between the range of motion (ROM) of the two groups	Box handling	– Participants lifted a crate weighing 3% of their MVC – The crate was 38 cm long, 34 cm wide and 28 cm tall, with handhold cut-outs 25 cm from the base – Participants lifted the crate with straight legs for 4 minutes at a rate of 15 lifts/min	– Force plate data was collected from ground – Electromagnetic motion sensors collected position and orientation data in order to determine the % of lumbar angle ROM

Yang et al. 2007	N = 4 novices – University students – Inexperienced lifters	N = 6 experienced – Local shipping and distribution centers and grocery store employees – ≥ 1 year of full-time employment in lifting job	N = 10 – No health conditions or previous low back pain – No sig. difference in demographic data between groups	Box handling	– Participants lifted a box from a stand (88 cm high) and placed it on a conveyor (121 cm high) 90° to the right – Participants lifted the boxes for an 8-hour workday with two 15 min and a 30 min break, or until exhaustion (whichever came first) – Participants randomly assigned to a load level of either 1.1, 4.9 or 11.7 kg – Participants were tested on 5 separate days at their load level for 5 different lifting frequencies (2, 4, 8, 10 and 12 lifts/min) – Participant lifted the boxes according to a computer-generated tone for each frequency	– Regional muscle oxygen saturation was measured using the INVOS® 4100 Cerebral Oximeter (Somanetics Corporation, Troy, MI, USA) – Regional oxygen saturation index (rSO_2) is the percentage of oxygenated hemoglobin relative to the total hemoglobin

*Sig. difference = significant difference, MMH = manual material handling, IMU = inertial measurement units, MVC = maximal voluntary contraction, EMG = electromyography

Table 22: Biomechanical Analysis of Novice versus Expert Manual Handling Strategies: Study and Task Description

Study	Inexperienced Workers	Experienced Workers	Participants	Task	Task Description	Methods
Alwasel et al. 2017a	N = 16 inexperienced workers – N = 5 Novices (<1 year experience) – N = 4 First year apprentices (1 year experience) – N = 7 Third year apprentices (3 years experience)	N = 5 Journeymen – >5 years experience – 5x experience of the other groups	– N = 21 masons	Block handling	– Lay down 45 concrete blocks with mortar on top of a lead wall to build a standard wall 6 rows high	– Motion capture (IMU suit) and video cameras
Alwasel et al. 2017b	– Same as Alwasel et al. 2017a	– Same as Alwasel et al. 2017a	– Same as Alwasel et al. 2017a	Block handling	– Same as Alwasel et al. 2017a	– Motion capture (IMU suit) and video cameras – Machine learning algorithm for pose classification of all experience groups
Authier et al. 1996	N = 6 Novices – 3+ months handling experience – Mean experience = 0.7 years – Physical education students	N = 6 Experts – Selected as experts by coworkers and management – Mean experience = 20 years – Incidence rate for accidents was 6x lower than the average incidence rate of the company – Employed at a large transportation company	N = 12 – No sig. differences between groups for mass, height, maximal muscular extension moment at the back	Box handling	– Transfer 3 sets of 16 boxes (Stacked 2x2x4) from a platform to a cart placed perpendicular to one another. o 8 boxes = 12 kg o 8 boxes = 22 kg	– Filmed using 2 video cameras with perpendicular views of the subjects. Floor was divided into 16 cm square grid with an x, y coordinate system. Heel was used as a reference point. – Analyzing MMH techniques

Authier et al. 1995	– Same as Authier et al. 1996 – Mean age: 23	– Same as Authier et al. 1996 – Mean age: 40	– Same as Authier et al. 1996 – Ages sig. different	Box handling	– Transfer 3 sets of 16 boxes (Stacked 2x2x4) from a platform to a cart placed perpendicular to one another. ○ 8 boxes = 12 kg ○ 8 boxes = 22 kg – Pickup heights: 33cm, 64cm, 95 cm, 126 cm – Boxes picked up from 126cm were placed at 33 cm and vice versa, and those at 95cm were placed at 64cm and vice versa	– Filmed using 2 video cameras with perpendicular views of the subjects. – Analyzing the effect of weight and height on MMH techniques
Gagnon et al. 1996	N = 5 Novices – 5 male physical education students – Inclusion criteria: ≥ 3 months handling experience and working in a different company than the experts – Mean experience = 0.7 years (Range: 0.3-0.9)	N = 6 Experts – Transportation workers – Experts identified by peers and managers as having the best manual handling skills – Inclusion criteria: ≥ 10 years experience and no current shoulder or back MSDs – Mean experience = 20 years (range: 14-36) – Experts had lower annual rate of handling accidents (0.13) compared to the rest of the firm (0.83)	N = 11 – No significant differences between the groups for the maximum strength of trunk extensors, flexors or right rotators – Experts had a mean age of 40 with a range between 32-56 whereas novices had a mean age of 23 with a range between 20-27	Box handling	– Transfer 12 and 22 kg loads from 4 different initial low positions to a low platform	– Force platforms on ground – Cameras and mirrors to determine 3D kinematic data – Back strength measured using dynamometer at 40° of sagittal flexion (trunk extensors, flexors and right rotators)

Plamondon et al. 2010	N = 15 novices – 3-6 months handling experience – Mean years of experience = 0.5 (0.4) – No injury in preceding year	N = 15 experts – ≥ 5 years of experience – Mean years of experience = 15.4 (9.3) – Low incidence of injuries and no injury in preceding year – Recommended by peers, union or managers (unknown how strict the recruiter was in applying this criteria)	N = 30 males – No MSDs that could affect normal work performance – No significant difference in weight, height or horizontal trunk moment weight at L5/S1 – Significantly different greater ages and years of experience for the expert group	Box handling	– Transfer 4 boxes (one at a time) from a conveyor at a height of 0.12 m to be stacked onto a hand trolley at a height of 0.02m from the ground and at a distance of 1.5 m from the initial location – The participant would also do the reverse: transfer the stacked boxed from the hand trolley back to the conveyor – Two conveyor positions: o Facing the trolley o 90° to the trolley o Both at a distance of 1.5 m – Four different load characteristics: o 15 kg o 23 kg o Weakened 15 kg box (12 bottles of sand and water with no cover) o 23 kg off-centre (centre of gravity 27 cm laterally from one side and 8 cm from the other) – Total of 128 box transfers for each participant o 4 boxes x 4 heights x 2 orientations x 2 trips x 2 repetitions	– Passive optoelectronic motion capture system – Video cameras – Force platform on ground – Synchronization system
Plamondon et al. 2012	– Same as Plamondon et al. 2010	– Same as Plamondon et al. 2010	– Same as Plamondon et al. 2010	Box handling	– Same as Plamondon et al. 2010	– Same as Plamondon et al. 2010

Plamondon et al. 2014	– Same as Plamondon et al. 2010	– Same as Plamondon et al. 2010 – 10 experts recruited from distribution centers, 5 from stores	– Same as Plamondon et al. 2010	Box handling	– Transferring 24 15-kg boxes (26 x 35x 32 cm) from one pallet to another and back, both at a height of 0.16 m – This was done 5 times during 30 minutes for a total of 240 box transfers – The boxes were stacked in 2 rows of 3 boxes, each 4 boxes high – The stacking of the boxes created 4 layers at heights of 0.16, 0.48, 0.8 and 1.12 m – For the first 2 trials, the task was self-paced (at a rate comfortable for an 8-hour workday) – For the last 3 trials were completed at a rate of 9 boxes/min	– Same as Plamondon et al. 2010 – Fatigue estimated using EMG, heart rate and Borg's scale – Localized muscular fatigue measured during the protocol with a standardized isometric sub-maximal task using surface EMG

*Sig. difference = significant difference, MMH = manual material handling, IMU = inertial measurement units, MVC = maximal voluntary contraction, EMG = electromyography

Table 23: Comparison of Novice versus Experienced Worker and Expert Trunk Kinematics for MMH Tasks

Study	Trunk Kinematics for Experienced Workers	Study	Trunk Kinematics for Expert Workers
Granata et al. 1999	– Experienced workers produced ▼ range of motion in the sagittal plane and sagittal velocity, especially in the faster than preferred condition – Experienced workers produced ▼lower peak lateral velocity and acceleration variabilities	Alwasel et al. 2017b	– First and third year apprentices have greater trunk inclination than experts
Hodder et al. 2010	– Experienced nurses maintained a relatively neutral posture throughout the patient reposition task from the side of the bed – Experienced nurses had ▼ lateral right bend displacement and sagittal and axial twist ROM than untrained novices in the patient reposition task from the side of bed – Experienced nurses had ▼ sagittal and axial ROM and ▲ left twist ROM than novices in the patient reposition task from the head of bed – Experienced nurses had ▼ maximum twist ROM than novices in the bed-to-wheelchair patient transfer task	Authier et al. 1996	– No difference
Lee and Nussbaum 2012	– Experienced workers had ▲ twisting angles during symmetric conditions – Experienced workers ▲ peak flexion/extension and lateral bending lumbar angular accelerations – Experienced workers had ▲ peak lateral bending angular accelerations while lowering in the asymmetric condition	Authier et al. 1995	– Experts more often had greater trunk inclination for lower boxes compared to higher boxes
Lee and Nussbaum 2013	– Previous study (Lee and Nussbaum 2012) revealed that experienced workers completed symmetric and asymmetric lifting with ▲ peak torso kinematics (angles, velocities, accelerations) and kinetics – Experienced workers had ▼ largest Lyapunov exponents (increased torso movement stability)	Gagnon et al. 1996	– No significant differences for trunk postures

Lee et al. 2014a	– Fatigue induced changes in peak torso angles, angular velocity of acceleration (flexion/extension, lateral bending or twisting) were not significantly different between groups – Experienced workers had a significant negative association of pre-fatigue lateral bending angular velocity with change in peak angular velocity (due to fatigue) – Fatigue reduced group differences in torso twisting velocities and accelerations – No significant effect of experience on largest Lyapunov exponent (torso stability)	Plamondon et al. 2010	– Experts had ▼ lumbar flexion angle and upper trunk flexion angle from vertical during both phases, ▼ lumbar flexibility index (%) during the deposit phase and ▲ lumbar torsion angle during the lifting phase at the time of peak resultant moment – Experts had ▲ lumbar torsion angle and ▼ lumbar flexion angular velocity during the lifting phase at the time of peak resultant moment – Experts had ▼ maximum upper trunk flexion range from vertical – No significant difference for lumbar lateral bending angle at the time of peak resultant moment – No significant difference for upper trunk flexion range
Lee et al. 2014b	– Experienced workers had ▼ twisting angles during pulling task – Experienced workers had ▼ lateral bending angular velocities and twisting angular accelerations at the preferred handle height – Experienced workers also had ▼ lateral bending angular velocity at elbow handle height in the push task	Plamondon et al. 2012	– Expertise had a significant effect on posture variables (lumbar flexion angle, trunk inclination and left knee angle)
Riley et al. 2015	– Novice lifters ▲ kyphotic lifting posture during extension and flexion phases of lift compared to experienced lifters – Novice lifters began the flexion phase of the lift near the middle of their ROM (58.6%) but ended the flexion phase closer to the end of their ROM (84.2%) – Novice lifters spent most of the extension phase in a kyphotic posture (88.6-91.9%) but ended the lift in a more neutral posture (70.6%) – Experienced lifters maintained a lordotic posture during the flexion phase and became more neutral, and maintained a neutral posture for most of the lift in the extension phase – No significant effect of gender	Plamondon et al. 2014	– Experts had ▼ lumbar flexion angles, lumbar flexibility indices and trunk inclinations at the time of the peak resultant moment – No significant difference in trunk asymmetry

Significantly increased/greater ▲ or decreased/lower ▼
Non-significantly increased/greater △ or decrease/lower ▽
No sig. difference = no significant difference

Table 24: Comparison of Novice versus Experienced Worker and Expert Trunk Kinetics for MMH Tasks

Study	Trunk Kinetics for Experienced Workers	Study	Trunk Kinetics for Expert Workers
Granata et al. 1999	– Experienced workers ▲ peak trunk moments (sagittal, lateral and twisting moments), spinal compression, anteroposterior shear and lateral shear forces on the lumbo-sacral region of the spine – Experienced workers had ▲sagittal and twisting moment variability, but this increase was proportional to the moment magnitudes generated by the experienced workers – Novices produced ▲lateral moment variability in the sagittally symmetric condition than during the asymmetric condition – Experienced workers generated ▲ spinal load variabilities for lateral shear, anteroposterior shear and compressive forces (spinal variability was more than could be attributed to a proportional increase in mean values associated with the experienced workers)	Alwasel et al. 2017a	– Third year apprentices had highest L4-L5 joint compression force and L5-S1 moment – Experts had lowest L4-L5 joint compression force – Differences between experts and third year apprentices were exacerbated when working close to the ground (1st course) – Normalized L4-L5 joint compression force and normalized L5-S1 moment peak at 3 years of experience and then decrease (inverse U trend)
Lee and Nussbaum 2012	– Experienced workers had ▲ peak flexion/extension lumbar moments compared to novices especially during lifting – No significant effects of experience on cumulative lumbar moments – Experienced workers experienced peak flexion/extension moments earlier in the lift and lateral bending moments later in the lift compared to novices	Gagnon et al. 1996	– No significant differences for trunk moments (extension moments, torsion and lateral bending moments)
Lee and Nussbaum 2013	– Previous study (Lee and Nussbaum 2012) revealed that experienced workers completed symmetric and asymmetric lifting with ▲ peak torso kinetics (moments) – Experienced workers had ▼ mean peak angular momenta in the X, Y and Z directions during asymmetric lifts – Experienced workers had ▽mean peak linear momenta in the X, Y (significant) and Z directions during asymmetric lifts – During symmetric lifts, experienced workers had comparable peak linear momenta in the X and Y directions compared to novices, but ▲ linear momentum in the Z direction	Plamondon et al. 2010	– No significant difference for peak L5/S1 resultant moment but peak L5/S1 resultant moment occurred ▼ sooner (% of flight time) in experts during the lifting phase – No significant differences for max extension, peak L5/S1 asymmetrical, and max and min lateral bending moments – Experts had significantly ▲ max torsion moment and ▼ min torsion moment
Lee et al. 2014a	– Experienced workers had ▲ peak twisting moments post-fatigue compared to novices – Novices had ▼ peak lateral bending moments post-fatigue compared to pre-fatigue and experienced workers – Experienced workers had ▲ cumulative lateral bending and twisting moments post fatigue compared to novices who had consistent cumulative moments pre and post fatigue	Plamondon et al. 2012	– Lifting height and weight had a greater effect size than expertise on external back loading variables (moments) whereas expertise had low impact

Lee et al. 2014b	– No significant effect of experience on peak or cumulative moments – Significant interaction effect of experience and task type for the peak lateral bending and twisting moment o Experienced workers had △ peak lateral bending moments during pushes and ▽ during pulls and the opposite for peak twisting moments o Experienced workers had △ cumulative lateral bending moments during pushes and ▽ during pulls and the opposite for cumulative twisting moments	Plamondon et al. 2014	– No significant difference for the peak resultant moment at L5/S1, peak asymmetrical moment at L5/S1 or cumulative loading – Experts had ▽ mean values for peak resultant moment at L5/S1 at higher lifting heights (significant interaction effect of expertise and height)
Marras et al. 2006	– Experience had a significant effect on lumbar compression forces – Significant interaction effect of moment*experience on lumbar compression forces – Experienced subjects had 13% compressive loads on average, but the spinal compression was only ▼ for the 8 Nm moment – Regardless of moment exposure, novices had similar compressive loads on the spine, whereas experienced workers experienced increased spinal compression as the moment increased – Significant interaction effect of moment*experience*frequency on lumbar lateral shear forces – In novices, the highest and lowest moments produced the greatest lateral shear, and the lowest at the moderate moment exposure (except for at the 8 lifts/min frequency) – In experts, the peak lateral shear value was 28% ▽ than the peak value for the novice group and the moderate moment exposure produced the greatest lateral shear at 4 and 6 lifts/min		

Significantly increased/greater ▲ or decreased/lower ▼
Non-significantly increased/greater △ or decrease/lower ▽
No sig. difference = no significant difference

Table 25: Comparison of Novice versus Experienced Worker and Expert Stepping Strategies and Foot Positioning for MMH Tasks

Study	Stepping Strategies and Foot Positioning for Experienced Workers	Study	Stepping Strategies and Foot Positioning for Expert Workers
Lee and Nussbaum 2012	– Experienced workers placed their feet ▲distance (~5 cm) from the box in the sagittal plane	Authier et al. 1996	– Experts took more steps during the transfer – Experts rarely pivoted – Experts began and ended the lift with their body weight on one foot
		Authier et al. 1995	– Experts more often stood on both feet when transferring the low boxes compared to higher boxes – Experts sometimes pivoted their feet for low boxes compared to the other heights – Experts only pivoted when they started the transfer with weight on both feet – Experts more often took more steps when transferring higher boxes compared to lower boxes – For low boxes experts more often placed their feet close to the deposit location compared to other heights
		Gagnon et al. 1996	– Feet mobility observed for both expert and novice group (no significant differences)

Significantly increased/greater ▲ or decreased/lower ▼
Non-significantly increased/greater △ or decrease/lower ▽
No sig. difference = no significant difference

Table 26: Comparison of Novice versus Expert Knee Kinematics and Kinetics and Hips and Body Positioning for MMH Tasks

Study	Knee Kinematics and Kinetics for Expert Workers	Study	Hips and Body Positioning for Expert Workers
Alwasel et al. 2017a	– Experts had the lowest knee moments	Authier et al. 1996	– Experts' pelvises less often faced the platform at the beginning of transfer (supporting foot and pelvis towards deposit site) – Experts positioned themselves closer to the platform before transfer
Authier et al. 1996	– Experts bent knees less often at beginning and end of transfer	Authier et al. 1995	– Experts more often positioned their pelvis towards the deposit location for lower boxes compared to other heights
Authier et al. 1995	– Experts bent their knees more when lifting lower boxes compared to higher boxes and more often to a greater degree (<100°) compared to novices	Plamondon et al. 2010	– Experts had ▼min height of (subject's) center of gravity during the lifting phase
Gagnon et al. 1996	– Experts had ▼ axial and peak left knee moments – Experts had ▼ knee flexion and total excursion of the left lower limb – Experts had a tendency to assume straighter leg position with minimum knee movement		
Plamondon et al. 2010	– Experts had ▲ left knee flexion during both phases and ▲right knee flexion during the lifting phase at the time of peak resultant moment – No significant difference for right knee flexion range – Experts had ▲max left and right knee flexion and left knee flexion range in the lifting phase		
Plamondon et al. 2014	– Experts bent knees ▲ more during lifting phase while boxes were close to the group		

Significantly increased/greater ▲ or decreased/lower ▼
Non-significantly increased/greater △ or decrease/lower ▽
No sig. difference = no significant difference

Table 27: Comparison of Novice versus Expert Hands and Load Positioning for MMH Tasks

Study	Hand Positioning for Expert Workers	Study	Load Positioning for Expert Workers
Authier et al. 1996	– Experts used diagonal grips or asymmetric grips (rarely used symmetrical grips) – Experts more often held the box at the corners – Novices more often had a least one hand flat on the face of the box	Alwasel et al. 2017b	– Experts carry the load closer to the torso
Authier et al. 1995	– Experts more often used diagonal grips for lower or medium boxes compared to an asymmetric grip for higher boxes – Experts more often modified grips when lifting from high to low rather than low to high or middle heights – Experts changed their grip least when transferring boxes between the middle heights compared to other heights – Experts more often held boxes at their edges when depositing at high heights but more often held boxes at the corner or edge for the lower or middle heights	Authier et al. 1996	– Experts more often moved the box closer to them during the preparation phase – Experts more often rotated the box in the direction of the deposit site – Experts more often tilted the box/pivoted the box onto one edge or corner and carried the boxes while tilting them – Experts more often tilted the box to the right than the left
Plamondon et al. 2010	– No significant difference for horizontal hand distance to L5/S1 (m) at the time of peak resultant moment – Experts had ▼ maximum vertical hand distance to L5/S1 during both phases and ▼ maximum horizontal hand distance to L5/S1 during the lifting phase	Authier et al. 1995	– Weight of load did not influence the frequency at which experts brought the box closer to themselves – Experts more often tilted heavier boxes forward at deposit compared to lighter boxes – Novices more often supported the heavier boxes on their bodies than lighter ones (Experts did not) – Experts less often moved high boxes (126cm) closer before transfer compared to lower boxes – Experts more often tilted higher boxes forward and lower boxes to the right compared to other heights
Plamondon et al. 2014	– Experts had ▼ hand distance to L5/S1		

Significantly increased/greater ▲ or decreased/lower ▼
Non-significantly increased/greater △ or decrease/lower ▽
No sig. difference = no significant difference

Table 28: Comparison of Other Factors for Novice versus Experienced Workers and Experts during MMH Tasks

Study	Other Factors for Experienced Workers	Study	Other Factors for Expert Workers
Hodder et al. 2010	– Experienced nurses had ▽ peak activity in right external oblique and left posterior deltoid activity than novices, and ▲ left trapezius and △ right trapezius activity than trained novices in the patient reposition task from the side of bed – Experienced nurses had ▲ left trapezius, left and right external oblique muscle activity than trained novices but no significant differences in muscle activity compared to untrained novices in the patient reposition task from the head of bed – Experienced nurses had ▼right erector spinae activity, ▽ left external oblique activity and △ left and right rectus femoris acitvity than untrained novices in the bed to wheelchair patient transfer task – Experienced nurses had ▽ right erector spinae activity and △ left and right rectus femoris activity compared to trained novices in the bed-to-wheelchair patient transfer task	Alwasel et al. 2017	– Third year apprentices had highest right shoulder moment – Experts had lowest left and right shoulder, elbow and hip moments – Differences between experts and third year apprentices were exacerbated when working close to the ground (1^{st} course) – There was a positive association between years of experience and productivity – Injury risk peaks at 3 years of experience and then decreases (inverse U trend) – Experts laid the most blocks per minute, followed by third year apprentices, then first year apprentices and lastly, novices
Lee and Nussbaum 2012	– Experienced workers had △ within and between-participant variance components for most measures compared to novices	Alwasel et al. 2017b	– Experts move more efficiently (fewer poses) – Experts laid twice the number of blocks/min
Lee and Nussbaum 2013	– Horizontal linear (Y and Z directions) and angular momenta (X, Y and Z directions) were ▼ in experienced workers which may indicate superior balance-maintenance strategies	Authier et al. 1995	– Experts more often increased momentum of heavier boxes during the lift compared to lighter boxes – Experts more often increased moment of boxes when lifting from low to high compared to other heights and transfers
Lee et al. 2014b	– No significant effects of experience on peak hand forces – Experienced workers pulled the cart with ~15% ▲ anteroposterior forces – Experienced workers had ▲ mean mediolateral hand forces during push and pulls (more substantial difference during pushes) – Experienced workers ▼ required coefficient of friction (slip risk) during pushes and higher during pulls compared to novices	Plamondon et al. 2010	– No significant difference for duration of transfer and path

Yang et al. 2007	– For the right and left erector spinae, experienced workers ▼ normalized oxygen saturation compared to novice subjects – During the 8-hour lifting task, the oxygen saturation of the left and right erector spinae of experienced workers increased by 8.8% and 10.3% from baseline, respectively – The oxygen saturation of the left and right erector spinae of novice subjects increased 16.7% and 15.1% from baseline, respectively – For the right erector spinae, experienced workers demonstrated an increasing trend of oxygen saturation from lower lift frequencies to higher lifter frequencies; however, novice subjects exhibited no trend	Plamondon et al. 2014	– No significant difference for perception of physical fatigue or back muscle fatigue – Experts had ▲ normalized heart rate (% of max heart rate) – No significant different for task duration, pre or post-flight time, flight time and path length

Significantly increased/greater ▲ or decreased/lower ▼
Non-significantly increased/greater △ or decrease/lower ▽
No sig. difference = no significant difference

Table 29: Summary of Study Results Analyzing the Biomechanics of Expert Strategies

Study	Participants	Expert Strategy Analyzed	Task Description	Methods	Results
Gagnon 1997	N = 7 – Inexperienced subjects (marginal handling experience) – Physical education students	Knee motions and box tilting during box handling	– Lift a 12 kg box in the sagittal plane (length × width × height; 40 cm × 26 cm × 25 cm) – Symmetrical lift from ground to shelf 67 cm above the ground – Self-selected foot spacing and distance, standardized hand grip on lateral edges – Three strategies: o Reduced knee flexion and backwards box tilt (expert) o Large knee flexion and backward box tilt o Large knee flexion and no box tilt (novice)	– Force plates – 3D motion capture	– Box tilt ▼20% average low back compression and ▼16% max shoulder flexor moments – Box tilt and reduced knee flexion ▼29% average low back compression and ▼26.3% max shoulder flexor moments – Box tilt and reduced knee flexion▼19.3% duration load supported (s) and ▼ 12.7% path of load supported (m) – Reduced knee flexion reduced ▼ 15.5% mechanical work, ▼ 80.5% max knee extensor moment, ▼ 12.5% max shoulder flexor moment, ▼ 13.3% low back extensor moment at pick-up, ▼ 10.2% max low back compression, and ▼ 11.5% average low back compression
Delisle et al. 1996a	N=14 novices – Healthy male college students – 3-14 months manual handling experience	Box tilting during box handling	– All tasks executed with the feet fixed 57 feet apart – Move a 12 kg box (32 cm × 32 cm × 46 cm) from a 16 cm shelf to another 16 cm shelf 90° to their left – Hands were places on diagonally opposite corners – Boxes were tilted to the right, left, backwards or without a tilt	– Force plates – 3D motion capture (passive motion capture system – optoelectronic)	In comparison to the other tilting strategies: – Backwards tilt ▲ 54.6-82.1% right lateral bending moment compared to left tilt or flat, it also changed the direction of lateral bending moment from -22 Nm left to 51 Nm right compared to right tilt – Backwards tilt ▼ 6.8-7.7 resultant trunk and ▼ 9.4% trunk extension moments and ▼ 55.6-77.78% left torsion angle – Backward tilt ▼ 33.3-46.7% asymmetry between pelvis and shoulders – Right tilt created a left lateral bend moment (22 Nm) and ▲ 38.7-350% left torsion angle – Left tilt ▼ asymmetry of grip by 15.242.9% relative to pelvis and by 82.4-87.0% relative to shoulders at deposit – Left tilt ▼ 19.1-22.5% stability at deposit compared to a right tilt or flat (no tilt)

Delisle et al. 1996b	N = 8 – Healthy male college students – 2-9 months manual handling experience	Foot step strategies during box handling	– Lifting and lowering a 12-kg box (32 cm × 32 cm × 46 cm) between a height of 1.2m and 0.1m at a 90° to the right – Horizontal distance of the box at the start of the task to the final position was 2 m – Executed using two footstep strategies associated with experienced workers – Minimal feet displacement strategy (oblique-step) and a larger foot displacement strategy with a step (crossed-step) – Normal and accelerated condition – Standardized grip on box	– 3D motion capture – Inverse dynamics analysis	In the lifting task: – The oblique-step strategy ▼ 11.8% duration of the supporting phase, ▼ 10.1% the length of the paths of the box, ▼ 31.3% the length of the global center of gravity, ▼ 15.8% trunk excursion in flexion/extension, ▼ 46.3% shoulder/pelvis, 57.5% grip/pelvis and 25% grip/shoulders excursions and ▲ 34.5% excursion of the pelvis/feet angle compared to the crossed-step strategy – Interaction effect of accelerated lifting and footstep strategy: ▼ duration of supporting phase, length of path of the global center of gravity, and ▲ of maximal box velocity in the accelerated lifting condition were greater for the crossed-step strategy In the lowering task: – The oblique-step strategy ▲ 63.2% pelvis/feet, 77.8% shoulders/pelvis, 67.9% grip/pelvis excursion angles and ▲-1100% pelvis/feet, -400% shoulders/pelvis, 288.9% grip/pelvis orientation angles compared to the crossed-step strategy – The accelerated condition ▲ the maximal box acceleration more in the oblique-step strategy and ▲ the maximal L5/S1 resultant moment more in the crossed-step strategy

Delisle et al. 1998	N = 14 – Healthy male college students – 2-14 months manual handling experience	Knee flexion and lateral foot spacing during box handling	– Transfer a 12-kg box 90° to the right between two low shelves at a height of 0.16m – Two fixed positions of the feet were imposed: narrow (0.41 m apart) or large base of support (0.57 m apart) – Right and left ankle at lift/deposit were ~0.35 from the box – Two conditions for knee flexion: slightly flexed (~25°) and deeply flexed (~65°) knees – Standardized grip on box	– 3D motion capture – Force platforms on ground	– Width of base of support had no significant effects on trunk or knee orientations and trunk or knee moments, except for trunk torsion at deposit (narrow base ▼ 10.53% trunk torsion) – The large base of support ▲8.3% the overall mean destabilizing force (N) and ▼ 40.5% destabilizing force orientation (°) at deposit – Deeply flexed knees (~65°) ▼ 75% trunk torsion at pickup, 200% trunk lateral inclination at pickup and 100% at deposit and ▲ 96-178.3% knee flexion and 233.3-475% internal rotation at pickup and deposit – Deeply flexed knees (~65°) ▲ 7% trunk resultant and 6.6% flexion moments at pickup and ▲6.22% and 5.8% trunk resultant and flexion moments at deposit, respectively – Deeply flexed knees (~65°) ▲ magnitude of the lateral bending moment to the left from 4 to -21 Nm at pickup and from -12 to -26 Nm at deposit – Deeply flexed knees (~65°) ▼ 29.2-71.8% knee resultant and flexion moments at pick-up and deposit – Deeply flexed knees (~65°) ▲ 10.3% the overall mean destabilizing force (N), 15.9-21.3% the destabilizing force (N) at pickup and deposit and 14.3% the destabilizing force orientation (°) at pickup

Delisle et al. 1999	N = 8 – Healthy male college students – 2-9 months manual handling experience	Foot step strategies during box handling	– Lifting and lowering a 12-kg box (32 cm × 32 cm × 46 cm) between a height of 1.2m and 0.1m at a 90° to the right – Horizontal distance of the box between the start and end of the task was 2 m – Executed using two footstep strategies associated with experienced workers (oblique-step and crossed-step) and two footstep strategies associated with novice workers (large-step and backward-step) – Standardized grip on box	– 3D motion capture – Force platforms on ground used to validate the model – Inverse dynamics analysis	– The backward-step strategy ▲ 14-100% length of the subject's centre of gravity path and 25-58.8% duration compared to all other strategies and ▲ left trunk torsion angle (16°) in the lowering task at pickup compared to all other strategies (7-11° right trunk torsion) – The oblique-step strategy had ▼ 8.5-24.8% length of the path of the box and 29.0-50.0% subject's center of gravity – The backward-step strategy had generally ▲ angles of asymmetry in the upper body (absolute difference between 5-32° shoulder/pelvis and between 9-43° grip/pelvis) at pickup for lifting and lowering – The crossed-step strategy often had ▼/▽ angles of asymmetry between most segments (between 36-54° at shoulders/feet, 9-25° at pelvis/feet, 24-32° at shoulders/pelvis, 28-43° at grip/pelvis and 2-12° at grip/shoulders) at deposit for lifting and lowering – The crossed-step strategy had trunk torsion to the right opposed to the left in other strategies during lifting and lowering, and ▼11-14° trunk lateral bending to the right during lowering at deposit as opposed to the other strategies – Trunk resultant moments were not significantly different between strategies – The L5/S1 resultant moments were ▼ 16.2-22% for the crossed-step and backward-step strategies during lifting at deposit and ▲ 5.8-8.6% for the oblique-step strategy during lowering (△ 4.7% compared to the backward step) at deposit and ▲ 28.2% for the oblique-step during lifting at deposit (△ 7.4% compared to the large step)

Significantly increased/greater ▲ or decreased/lower ▼
Non-significantly increased/greater △ or decrease/lower ▽
No sig. difference = no significant difference

Table 30: Results of Studies Analyzing Training Based on the Observation of Expert Strategies

Study	Participants	Task	Task Description	Methods	Training Description	Training Outcomes
Gagnon 2003	N = 10 Novices – College students – 3-12 months occupational manual handling experience	Box lifting	– Lifting 15 kg boxes (30 cm × 42 cm × 33 cm; Height × Width × Depth) – 3 homogenous boxes (center of gravity at the center of the box) – 2 heterogeneous boxes (center of gravity off centered; 30% anterior and 86% superior) – Lifting between 2 shelves 22 cm above the ground, 1.6m and 90° perpendicular to the left	– 3D kinematic data recorded with 5 video cameras – Force plate – Analyzed with 3D biomechanical model	– 1 training session limited to homogenous boxes – Education on biomechanical principles – Video on expert versus novice manual handling strategies and verbal feedback sessions – Practice (encouraged to try different strategies) with feedback limited to first trials only – 'Search approach'	– ▼ 37.7-50% mechanical work on load and ▼ 22.7-31.9% net low back moment (at deposit only) for trained task – ▼ 43.4-48.1% mechanical work on load and up to ▼ 10.5% net low back moment (at take-off only) for analogous lifting task – No sig. difference for asymmetrical moments
Gagnon 2005	N = 10 Novices	Box lifting	– Lifting homogenous and heterogeneous 15 kg boxes	– 3D kinematic data recorded with 5 video cameras – Force plate – Analyzed with 3D biomechanical model	– Control study on effects of free practice – Practice based on observing expert workers' strategies	– No sig. difference for mechanical work, back efforts, back asymmetries or L5/S1 resulting moment when novices engaged in free practice without any instruction – Novices were able to learn expert strategies and adopted safer maneuvers after observing expert strategies (Reported in Gagnon, 2003)

Significantly increased/greater ▲ or decreased/lower ▼
Non-significantly increased/greater △ or decrease/lower ▽
No sig. difference = no significant difference

Appendix C
Predictor Screening Results

Table 31: Top Contributors Towards Forces at the L4/L5 Joint

	L4/L5 Compression		**L4/L5 Anterior/Posterior Shear**		**L4/L5 Lateral Shear**	
Rank	Joint Angle	%	Joint Angle	%	Joint Angle	%
1	Torso Flexion	24.7	Torso Flexion	18.7	Torso Flexion	25.9
2	Vertical Carrying Distance	16.3	Vertical Carrying Distance	15.6	Vertical Carrying Distance	20.3
3	Anterior Carrying Distance	12.2	A/P Stance Distance	11.4	Right Hip Flexion	7.9
4	Neck Flexion	12.0	Left Hip Flexion	7.4	Neck Flexion	6.1
5	Left Wrist Deviation	4.9	Neck Flexion	5.7	Left Wrist Deviation	4.8
6	Left Hip Flexion	4.7	Experience Group	5.0	Left Hip Flexion	4.7
7	Right Shoulder Flexion	3.9	Right Hip Flexion	4.9	Anterior Carrying Distance	4.5
8	Course	3.0	Torso Side Bending	4.2	A/P Stance Distance	2.8
9	Right Hip Flexion	2.8	Course	3.3	Course	2.6
10	Experience Group	2.2	Left Shoulder Abduction	2.7	Right Shoulder Flexion	2.1
Total		86.7		78.8		81.5
11	A/P Stance Distance	2.0	Lateral Carrying Distance	2.5	Torso Side Bending	2.0
12	Left Shoulder Flexion	1.9	Left Wrist Deviation	1.9	Experience Group	1.9
13	Torso Side Bending	1.7	Right Shoulder Flexion	1.6	Lateral Carrying Distance	1.8
14	Left Wrist Flexion	1.1	Left Shoulder Flexion	1.5	Right Wrist Flexion	1.5
15	Right Wrist Flexion	1.0	Left Wrist Flexion	1.3	Left Shoulder Flexion	1.2
Total		94.4		87.6		89.9

Table 32: Top Contributors Towards Shoulder Moments

	Left Shoulder Moment		**Right Shoulder Moment**	
Rank	Joint Angle	%	Joint Angle	%
1	Vertical Carrying Distance	21.9	Vertical Carrying Distance	18.5
2	Torso Flexion	17.7	Torso Flexion	18.2
3	Right Hip Flexion	9.0	Right Shoulder Flexion	10.0
4	Left Shoulder Abduction	6.9	Left Hip Flexion	8.7
5	Neck Flexion	6.4	Neck Flexion	7.4
6	Left Hip Flexion	5.7	Right Hip Flexion	6.4
7	Anterior Carrying Distance	5.3	Anterior Carrying Distance	4.3
8	Left Shoulder Flexion	5.1	A/P Stance Distance	3.0
9	Lift type	3.6	Lift type	3.0
10	Lateral Carrying Distance	3.1	Left Shoulder Abduction	2.4
Total		84.7		81.7
11	Right Shoulder Flexion	2.1	Experience Group	1.9
12	Left Elbow Flexion	1.6	Left Shoulder Axial Rotation	1.9
13	Experience Group	1.6	Lateral Carrying Distance	1.7
14	Course	1.3	Right Shoulder Axial Rotation	1.7
15	Left Shoulder Axial Rotation	1.1	Right Shoulder Abduction	1.2
Total		92.3		90.1

Table 33: Top Contributors Towards L4/L5 Compression by Experience Group

	Novices		1st Year Apprentices		3rd Year Apprentices		Journeymen	
Rank	Joint Angle	%	Joint Angle	%	Joint Angle	%	Joint Angle	%
1	Torso Flexion	22.1	Torso Flexion	23.4	Torso Flexion	18.2	Vertical Carrying Distance	18.2
2	Vertical Carrying Distance	17.1	Vertical Carrying Distance	13.2	Vertical Carrying Distance	12.7	Torso Flexion	14.9
3	Left Hip Flexion	9.6	Anterior Carrying Distance	10.7	Neck Flexion	11.1	Anterior Carrying Distance	11.0
4	Anterior Carrying Distance	9.6	Right Hip Flexion	8.3	Anterior Carrying Distance	8.6	Neck Flexion	5.2
5	Right Hip Flexion	4.9	Left Hip Flexion	7.8	Left Wrist Deviation	8.0	Left Hip Flexion	4.7
6	Neck Flexion	4.5	Neck Flexion	7.3	Torso Side Bending	6.2	Right Hip Flexion	3.3
7	Right Wrist Deviation	4.0	Right Shoulder Flexion	3.0	Right Shoulder Flexion	5.1	Left Wrist Deviation	3.2
8	Left Wrist Deviation	3.6	Left Shoulder Flexion	2.8	Course	3.5	Lateral Carrying Distance	3.2
9	Right Shoulder Flexion	3.5	A/P Stance Distance	2.8	Left Hip Adduction/Abduction	3.5	Left Shoulder Flexion	3.1
10	A/P Stance Distance	2.2	Left Wrist Deviation	2.2	A/P Stance Distance	3.2	Right Shoulder Abduction	2.8
Total		81.1		81.4		80.0		69.4
11	Left Shoulder Abduction	2.2	Right Shoulder Abduction	2.0	Left Wrist Flexion	2.7	Right Wrist Flexion	2.6
12	Course	2.0	Course	1.6	Right Wrist Deviation	2.4	Neck Side Bending	2.6
13	Lateral Stance Distance	1.3	Torso Side Bending	1.5	Right Hip Flexion	1.9	Right Shoulder Flexion	2.5
14	Left Shoulder Flexion	1.3	Left Shoulder Axial Rotation	1.5	Left Shoulder Flexion	1.5	Torso Side Bending	2.5
15	Right Hip Adduction/Abduction	1.2	Lateral Carrying Distance	1.2	Right Wrist Flexion	1.4	Course	2.2
Total		89.1		89.2		89.9		81.7

Table 34: Top Contributors Towards L4/L5 Anterior/Posterior Shear by Experience Group

	Novices		**1st Year Apprentices**		**3rd Year Apprentices**		**Journeymen**	
Rank	Joint Angle	%	Joint Angle	%	Joint Angle	%	Joint Angle	%
1	Torso Flexion	19.0	Torso Flexion	19.0	Torso Flexion	13.2	Vertical Carrying Distance	11.2
2	Right Hip Flexion	12.0	Vertical Carrying Distance	11.3	Vertical Carrying Distance	12.5	A/P Stance Distance	10.7
3	A/P Stance Distance	9.8	Left Hip Flexion	6.8	A/P Stance Distance	10.2	Torso Flexion	8.1
4	Vertical Carrying Distance	7.3	Right Hip Flexion	6.8	Neck Flexion	6.8	Left Hip Flexion	7.0
5	Left Hip Flexion	6.7	Neck Flexion	6.2	Left Hip Flexion	6.7	Left Shoulder Abduction	6.4
6	Torso Side Bending	4.4	Torso Side Bending	4.7	Right Hip Flexion	4.8	Course	4.6
7	Neck Flexion	4.2	Course	4.6	Left Wrist Flexion	3.9	Torso Side Bending	4.0
8	Left Shoulder Flexion	2.8	Neck Side Bending	4.5	Right Shoulder Axial Rotation	3.9	Right Hip Flexion	3.8
9	Anterior Carrying Distance	2.8	A/P Stance Distance	4.0	Left Wrist Deviation	3.5	Right Hip Adduction/Abduction	3.7
10	Lateral Carrying Distance	2.6	Left Shoulder Abduction	3.6	Torso Side Bending	3.2	Right Shoulder Abdu ction	3.5
Total		71.5		71.5		68.7		63.2
11	Right Shoulder Flexion	2.5	Lift type	3.2	Right Shoulder Abduction	2.8	Lateral Carrying Distance	3.5
12	Course	2.3	Right Hip Rotation	2.2	Lateral Carrying Distance	2.5	Anterior Carrying Distance	3.3
13	Left Hip Adduction/Abduction	2.0	Lateral Carrying Distance	2.2	Left Shoulder Flexion	2.5	Left Shoulder Flexion	2.7
14	L5S1 Axial Twist	2.0	Right Shoulder Abduction	1.9	Right Wrist Flexion	2.3	Neck Side Bending	2.6
15	Right Hip Adduction/Abduction	1.8	Right Shoulder Flexion	1.7	Right Shoulder Flexion	2.1	Left Hip Rotation	2.2
Total		82.2		82.7		80.9		77.4

Table 35: Top Contributors Towards L4/L5 Lateral Shear by Experience Group

	Novices		1st Year Apprentices		3rd Year Apprentices		Journeymen	
Rank	Joint Angle	%	Joint Angle	%	Joint Angle	%	Joint Angle	%
1	Torso Flexion	24.1	Torso Flexion	25.4	Torso Flexion	15.6	Torso Flexion	14.5
2	Vertical Carrying Distance	13.1	Vertical Carrying Distance	15.8	Vertical Carrying Distance	14.4	Vertical Carrying Distance	10.1
3	Right Hip Flexion	8.0	Right Hip Flexion	8.9	Neck Flexion	8.4	Anterior Carrying Distance	6.8
4	Anterior Carrying Distance	5.8	Left Hip Flexion	6.6	Right Hip Flexion	5.2	Left Wrist Deviation	6.1
5	Left Hip Flexion	5.7	Neck Flexion	6.0	Left Wrist Deviation	5.1	Left Hip Flexion	5.1
6	Right Shoulder Abduction	3.1	Anterior Carrying Distance	3.4	A/P Stance Distance	5.0	Neck Flexion	4.3
7	Course	2.9	Left Wrist Deviation	3.1	Anterior Carrying Distance	4.6	Right Shoulder Abduction	4.2
8	Left Shoulder Abduction	2.4	Torso Side Bending	2.5	Right Shoulder Flexion	4.2	Right Wrist Deviation	4.0
9	A/P Stance Distance	2.3	Left Shoulder Flexion	2.1	Left Hip Flexion	3.9	Right Hip Flexion	3.5
10	Right Wrist Deviation	2.2	Course	1.9	Course	3.9	Left Shoulder Abduction	3.1
Total		69.6		75.7		70.3		61.5
11	Lateral Carrying Distance	2.2	Left Shoulder Abduction	1.8	Lateral Carrying Distance	3.5	A/P Stance Distance	2.9
12	Left Elbow Flexion	2.0	Right Wrist Deviation	1.6	Right Shoulder Abduction	3.1	Lateral Carrying Distance	2.8
13	Lift type	1.9	Right Wrist Flexion	1.5	Torso Side Bending	2.6	Right Elbow Flexion	2.7
14	Torso Side Bending	1.8	A/P Stance Distance	1.3	Right Wrist Flexion	2.3	Left Hip Rotation	2.7
15	Neck Side Bending	1.8	Right Hip Adduction/Abduction	1.3	Left Wrist Flexion	1.9	Neck Side Bending	2.6
Total		79.3		83.2		83.9		75.2

Table 36: Top Contributors Towards Left Shoulder Moment by Experience Group

	Novices		**1st Year Apprentices**		**3rd Year Apprentices**		**Journeymen**	
Rank	Joint Angle	%	Joint Angle	%	Joint Angle	%	Joint Angle	%
1	Vertical Carrying Distance	16.8	Vertical Carrying Distance	25.4	Vertical Carrying Distance	20.8	Vertical Carrying Distance	23.9
2	Torso Flexion	14.8	Torso Flexion	9.7	Torso Flexion	18.5	Torso Flexion	13.6
3	Right Hip Flexion	11.6	Neck Flexion	6.5	Right Hip Flexion	12.8	Left Shoulder Abduction	9.7
4	Neck Flexion	10.3	Right Hip Flexion	5.5	Anterior Carrying Distance	6.7	Anterior Carrying Distance	6.7
5	Left Hip Flexion	6.2	Left Shoulder Abduction	5.3	Left Hip Flexion	6.6	Left Shoulder Flexion	6.0
6	Left Shoulder Flexion	4.1	Left Shoulder Flexion	4.6	Left Shoulder Flexion	5.1	Neck Flexion	5.8
7	Left Shoulder Abduction	4.0	Anterior Carrying Distance	4.1	Left Shoulder Abduction	4.7	Left Shoulder Axial Rotation	4.0
8	Lift type	3.8	Lateral Carrying Distance	4.0	Neck Flexion	3.3	Right Hip Flexion	3.7
9	Left Elbow Flexion	3.4	Lift type	3.9	Right Shoulder Flexion	2.5	Lateral Carrying Distance	2.6
10	Right Elbow Flexion	3.3	Course	3.4	Left Shoulder Axial Rotation	2.4	Right Shoulder Axial Rotation	2.5
Total		78.0		72.5		83.3		78.5
11	Left Wrist Deviation	2.1	Left Hip Flexion	3.0	Lateral Carrying Distance	2.3	Right Shoulder Flexion	2.2
12	Lateral Carrying Distance	1.8	Left Elbow Flexion	2.4	Lift type	2.1	Left Hip Flexion	2.1
13	L5S1 Axial Twist	1.6	Right Shoulder Flexion	2.3	Course	1.1	Lift type	1.9
14	Right Shoulder Flexion	1.5	Left Shoulder Axial Rotation	1.7	Right Shoulder Axial Rotation	1.0	Right Shoulder Abduction	1.7
15	Anterior Carrying Distance	1.5	Left Hip Adduction/Abduction	1.6	Left Elbow Flexion	0.9	Neck Side Bending	1.4
Total		86.6		83.5		90.8		87.9

Table 37: Top Contributors Towards Right Shoulder Moment by Experience Group

	Novices		**1st Year Apprentices**		**3rd Year Apprentices**		**Journeymen**	
Rank	Joint Angle	%	Joint Angle	%	Joint Angle	%	Joint Angle	%
1	Vertical Carrying Distance	17.9	Torso Flexion	16.3	Left Hip Flexion	18.7	Torso Flexion	22.9
2	Torso Flexion	11.7	Vertical Carrying Distance	13.3	Torso Flexion	16.4	Vertical Carrying Distance	21.4
3	Right Shoulder Flexion	6.8	Left Hip Flexion	8.1	Vertical Carrying Distance	11.9	Left Hip Flexion	8.8
4	Right Hip Flexion	5.4	Right Shoulder Flexion	6.7	Right Shoulder Flexion	9.8	Right Shoulder Flexion	8.3
5	Left Elbow Flexion	5.3	Lateral Carrying Distance	5.9	Right Hip Flexion	7.1	Right Shoulder Axial Rotation	4.7
6	Anterior Carrying Distance	5.1	Left Shoulder Abduction	5.1	Neck Flexion	5.4	Right Hip Flexion	4.2
7	Left Wrist Flexion	4.0	Neck Flexion	4.9	Anterior Carrying Distance	4.7	Neck Side Bending	3.3
8	Right Shoulder Abduction	3.7	Lift type	4.4	A/P Stance Distance	3.6	Anterior Carrying Distance	2.9
9	Left Hip Adduction/Abduction	3.2	Left Shoulder Axial Rotation	4.1	Right Shoulder Axial Rotation	2.4	Left Shoulder Flexion	2.7
10	Right Elbow Flexion	3.1	Right Shoulder Abduction	3.2	Left Wrist Deviation	2.3	Left Shoulder Abduction	2.3
Total		66.1		72.1		82.2		81.6
11	Torso Side Bending	3.0	Anterior Carrying Distance	2.9	Course	2.2	Neck Flexion	2.2
12	Neck Flexion	2.9	Left Shoulder Flexion	2.5	Left Elbow Flexion	1.7	Right Knee Flexion	2.0
13	Right Hip Adduction/Abduction	2.8	Right Shoulder Axial Rotation	2.5	Lift type	1.6	Left Shoulder Axial Rotation	1.7
14	Left Shoulder Axial Rotation	2.5	Right Hip Flexion	2.5	Left Shoulder Axial Rotation	1.2	Right Shoulder Abduction	1.3
15	Lift type	2.5	A/P Stance Distance	1.7	Right Wrist Flexion	1.1	Left Knee Flexion	1.1
Total		79.9		84.2		89.9		89.9

Appendix D
Summary of Probabilities of Mixed Effect Model for Entire Task

Table 38: Summary of Probabilities (> F values) for the Main and Interaction Effects of Experience Group and Course on Kinematic Variables Across Entire Task

Variable	Experience Group **Prob > F**	Experience Group* Course **Prob > F**
Neck Flexion	**<.0001**	**<.0001**
Neck Side Bending	**<.0001**	**<.0001**
Left Shoulder Flexion	**<.0001**	**<.0001**
Left Shoulder Abduction	**<.0001**	**<.0001**
Left Shoulder Axial Rotation	**<.0001**	**<.0001**
Right Shoulder Flexion	**<.0001**	**<.0001**
Right Shoulder Abduction	**<.0001**	**<.0001**
Right Shoulder Axial Rotation	**<.0001**	**<.0001**
Left Elbow Flexion	**<.0001**	**<.0001**
Right Elbow Flexion	**<.0001**	**<.0001**
Left Wrist Flexion	**<.0001**	**<.0001**
Left Wrist Deviation	**<.0001**	**<.0001**
Right Wrist Flexion	**<.0001**	**<.0001**
Right Wrist Deviation	**<.0001**	**<.0001**
Torso Flexion	**<.0001**	**<.0001**
Torso Side Bending	**<.0001**	**<.0001**
L5S1 Axial Twist	**<.0001**	**<.0001**
Left Hip Flexion	**<.0001**	**<.0001**
Left Hip Adduction/Abduction	**<.0001**	**<.0001**
Left Hip Rotation	**<.0001**	**<.0001**
Right Hip Flexion	**<.0001**	**<.0001**
Right Hip Adduction/Abduction	**<.0001**	**<.0001**
Right Hip Rotation	**<.0001**	**<.0001**
Left Knee Flexion	**<.0001**	**<.0001**
Right Knee Flexion	**<.0001**	**<.0001**
Anterior Carrying Distance	**<.0001**	**<.0001**
Vertical Carrying Distance	**<.0001**	**<.0001**
Lateral Carrying Distance	**<.0001**	**<.0001**
Lateral Stance Distance	**<.0001**	**<.0001**
A/P Stance Distance	**<.0001**	**<.0001**

*Significant effects denoted in bold (p<0.05).

Appendix E
Main of Effect of Experience Data Tables & Figures

Table 39: Mean Angles (°) and Distance (% Height) of Kinematic Variables for Entire Task

	Novices		**1st Year Apprentices**		**3rd Year Apprentices**		**Journeymen**	
	Mean	*Std dev*	Mean	*Std dev*	Mean	*Std dev*	Mean	*Std dev*
Neck Flexion	5.48	*16.31*	7.94	*19.31*	13.31	*19.30*	2.82	*17.17*
Neck Side Bending	3.63	*10.10*	0.68	*9.72*	1.01	*11.24*	-2.45	*12.68*
Left Shoulder Flexion	27.93	*21.55*	34.67	*29.27*	29.85	*26.42*	36.02	*26.50*
Left Shoulder Abduction	8.62	*18.11*	15.39	*18.15*	13.21	*17.37*	14.06	*19.97*
Left Shoulder Axial Rotation	28.15	*48.68*	22.61	*75.35*	24.32	*58.65*	28.45	*54.58*
Right Shoulder Flexion	26.22	*22.48*	34.87	*29.82*	32.92	*28.41*	37.85	*26.31*
Right Shoulder Abduction	14.79	*17.37*	12.22	*21.24*	17.79	*17.22*	13.76	*18.53*
Right Shoulder Axial Rotation	-23.13	*51.72*	-34.07	*69.81*	-36.41	*62.09*	-35.60	*59.22*
Left Elbow Flexion	55.23	*27.95*	54.59	*26.85*	48.15	*22.70*	46.38	*24.40*
Right Elbow Flexion	51.13	*25.73*	49.42	*25.85*	51.33	*23.98*	49.45	*23.77*
Left Wrist Flexion	-14.55	*36.14*	-21.58	*46.97*	-9.68	*32.96*	-14.15	*32.23*
Left Wrist Deviation	12.34	*22.95*	11.59	*28.25*	13.04	*26.87*	6.20	*23.25*
Right Wrist Flexion	-16.07	*38.20*	-14.26	*50.85*	-11.11	*48.68*	-13.96	*29.54*
Right Wrist Deviation	4.79	*26.65*	5.41	*30.35*	8.73	*28.03*	2.06	*20.65*
Torso Flexion	20.68	*24.63*	22.62	*27.84*	24.71	*29.04*	21.77	*23.90*
Torso Side Bending	-4.00	*35.59*	6.85	*38.70*	-2.48	*40.81*	5.68	*33.89*
L5S1 Axial Twist	0.19	*17.90*	6.02	*16.37*	1.32	*15.08*	0.87	*25.92*
Left Hip Flexion	32.19	*27.55*	27.57	*26.21*	25.63	*28.68*	34.83	*27.04*
Left Hip Adduction/Abduction	2.35	*12.41*	4.37	*12.70*	6.49	*11.57*	6.83	*11.68*
Left Hip Rotation	-3.99	*54.30*	-17.50	*44.10*	-17.94	*34.16*	-16.07	*48.22*
Right Hip Flexion	33.50	*27.81*	24.20	*26.22*	24.53	*28.39*	34.74	*28.66*
Right Hip Adduction/Abduction	8.07	*14.46*	4.29	*10.00*	8.38	*10.83*	2.71	*11.03*
Right Hip Rotation	20.21	*42.70*	22.44	*62.86*	19.79	*38.43*	5.34	*53.51*
Left Knee Flexion	20.86	*15.17*	23.66	*15.21*	23.60	*14.44*	24.98	*14.35*
Right Knee Flexion	21.93	*14.27*	20.15	*13.33*	22.51	*13.78*	23.81	*14.86*
Anterior Carrying Distance	16.53	*6.85*	17.67	*8.08*	15.19	*7.37*	19.08	*8.89*
Vertical Carrying Distance	-1.42	*11.77*	-0.71	*11.56*	-2.07	*11.25*	-1.80	*12.26*
Lateral Carrying Distance	2.12	*8.31*	-0.85	*8.23*	-0.76	*8.44*	-1.01	*9.25*
Lateral Stance Distance	16.16	*8.88*	14.54	*8.37*	17.50	*7.83*	15.54	*8.55*
A/P Stance Distance	1.15	*14.73*	2.13	*13.23*	-1.77	*15.64*	-5.19	*13.13*

Table 40: Main Effect of Experience on Mean Kinematic Variables Across Entire Task

	Novices		**1st Year Apprentices**		**3rd Year Apprentices**		**Journeymen**	
	Mean (% Absolute Max)	Significance Level	Mean (% Absolute Max)	Significance Level	Mean (% Absolute Max)	Significance Level	Mean (% Absolute Max)	Significance Level
Neck Flexion	41	A	60	B	100	C	21	D
Neck Side Bending	100	A	19	B	28	C	-67	D
Left Shoulder Flexion	78	A	96	B	83	C	100	D
Left Shoulder Abduction	56	A	100	B	86	C	91	D
Left Shoulder Axial Rotation	99	A	79	B	85	B	100	A
Right Shoulder Flexion	69	A	92	B	87	C	100	D
Right Shoulder Abduction	83	A	69	B	100	C	77	D
Right Shoulder Axial Rotation	-64	A	-94	B	-100	C	-98	D
Left Elbow Flexion	100	A	99	B	87	C	84	D
Right Elbow Flexion	100	A	96	B	100	C	96	D
Left Wrist Flexion	-67	A	-100	B	-45	C	-66	D
Left Wrist Deviation	95	A	89	B	100	C	48	D
Right Wrist Flexion	-100	A	-89	B	-69	C	-87	A
Right Wrist Deviation	55	A	62	B	100	C	24	D
Torso Flexion	84	A	92	B	100	C	88	D
Torso Side Bending	-58	A	100	B	-36	C	83	D
L5S1 Axial Twist	3	A	100	B	22	C	15	D
Left Hip Flexion	92	A	79	B	74	C	100	D
Left Hip Adduction/Abduction	34	A	64	B	95	C	100	D
Left Hip Rotation	-22	A	-98	B	-100	C	-90	C
Right Hip Flexion	96	A	70	B	71	C	100	D
Right Hip Adduction/Abduction	96	A	51	B	100	C	32	D
Right Hip Rotation	90	A	100	B	88	A	24	C
Left Knee Flexion	84	A	95	B	94	C	100	D
Right Knee Flexion	92	A	85	B	95	C	100	D
Anterior Carrying Distance	87	A	93	B	80	C	100	D
Vertical Carrying Distance	-69	A	-34	B	-100	C	-87	D
Lateral Carrying Distance	100	A	-40	B	-36	C	-48	D
Lateral Stance Distance	92	A	83	B	100	C	89	D
A/P Stance Distance	22	A	41	B	-34	C	-100	D

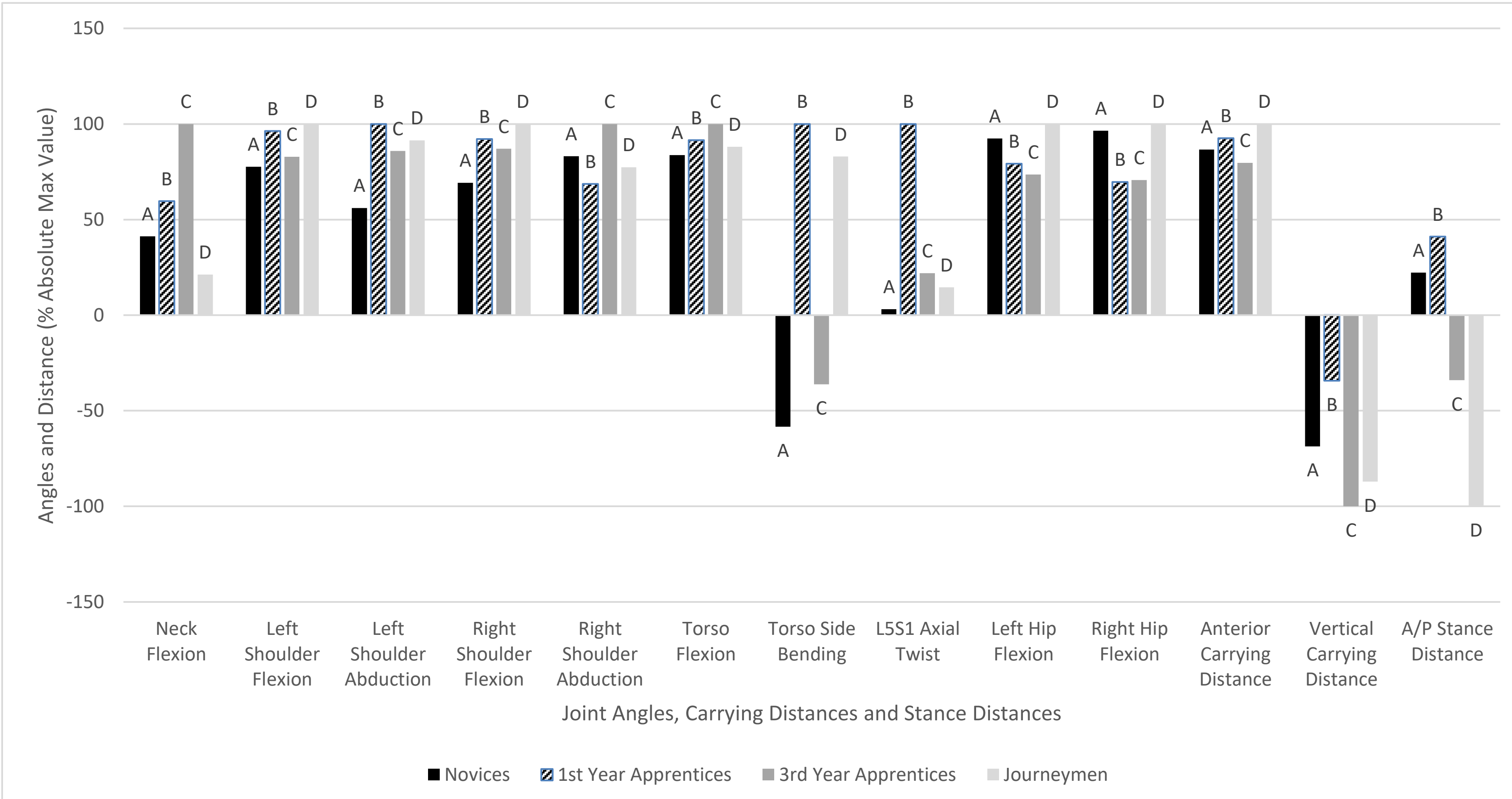


Figure 57: Effect of Experience on Postural Variables Across Entire Task

Table 41: Mean Angles (°) and Distance (% Height) of Kinematic Variables at Peak L4/L5 Compression Force

	Novices		**1st Year Apprentices**		**3rd Year Apprentices**		**Journeymen**	
	Mean	*Std dev*	Mean	*Std dev*	Mean	*Std dev*	Mean	*Std dev*
Neck Flexion	-1.26	*17.18*	0.68	*21.52*	6.65	*18.32*	-3.90	*18.02*
Neck Side Bending	4.18	*10.64*	0.04	*9.44*	1.40	*10.30*	-3.51	*16.19*
Left Shoulder Flexion	42.18	*21.25*	50.34	*24.29*	44.92	*25.22*	44.60	*27.34*
Left Shoulder Abduction	1.58	*18.96*	13.97	*19.40*	8.43	*19.62*	7.47	*21.23*
Right Shoulder Flexion	40.26	*21.72*	47.59	*28.49*	47.38	*29.39*	48.11	*24.62*
Right Shoulder Abduction	7.46	*18.26*	9.10	*22.24*	12.46	*17.14*	11.41	*20.42*
Right Shoulder Axial Rotation	-10.63	*49.09*	-27.90	*66.41*	-21.62	*66.39*	-17.36	*59.94*
Left Wrist Flexion	-1.86	*33.13*	-15.47	*46.68*	-2.28	*28.42*	-7.88	*31.30*
Left Wrist Deviation	15.87	*20.31*	13.06	*27.85*	14.55	*26.22*	10.92	*21.17*
Right Wrist Flexion	-9.75	*35.26*	-7.97	*50.07*	-6.22	*49.52*	-8.47	*30.53*
Right Wrist Deviation	9.31	*25.67*	6.17	*32.57*	10.71	*28.23*	5.20	*21.81*
Torso Side Bending	-4.33	*52.21*	14.29	*59.89*	-0.75	*61.03*	5.23	*50.67*
L5S1 Axial Twist	2.05	*18.14*	6.33	*15.96*	3.11	*16.75*	2.25	*26.42*
Left Hip Flexion	57.33	*28.52*	50.19	*26.80*	47.62	*30.15*	53.97	*26.57*
Left Hip Adduction/Abduction	2.36	*15.79*	5.62	*14.47*	7.43	*14.40*	7.42	*13.52*
Left Hip Rotation	-6.07	*48.71*	-14.32	*37.63*	-17.60	*32.17*	-13.99	*51.42*
Right Hip Flexion	59.53	*27.12*	44.77	*28.06*	46.75	*30.79*	55.89	*28.32*
Right Hip Adduction/Abduction	11.83	*16.68*	5.73	*11.83*	9.69	*13.41*	2.81	*12.44*
Right Hip Rotation	14.14	*43.36*	26.46	*53.15*	13.48	*34.94*	5.33	*55.96*
Anterior Carrying Distance	21.41	*6.14*	22.97	*6.86*	19.91	*6.68*	22.87	*8.42*
Lateral Carrying Distance	2.10	*9.81*	-1.13	*9.47*	0.14	*10.49*	1.00	*11.04*
Lateral Stance Distance	17.52	*9.20*	15.19	*8.79*	18.36	*8.84*	15.68	*9.09*
A/P Stance Distance	0.55	*16.71*	1.47	*15.22*	-1.46	*17.94*	-5.30	*14.87*

Table 42: Main Effect of Experience on Mean Kinematic Variables at Peak L4/L5 Compression Force

	Novices		1st Year Apprentices		3rd Year Apprentices		Journeymen	
	Mean (% Absolute Max)	Significance Level	Mean (% Absolute Max)	Significance Level	Mean (% Absolute Max)	Significance Level	Mean (% Absolute Max)	Significance Level
Neck Flexion	-19	A	10	A	100	B	-59	C
Neck Side Bending	100	A	1	B	33	C	-84	D
Left Shoulder Flexion	84	A	100	B	89	B	89	B
Left Shoulder Abduction	11	A	100	B	60	C	53	C
Right Shoulder Flexion	84	A	99	B	98	BC	100	C
Right Shoulder Abduction	60	A	73	B	100	B	92	B
Right Shoulder Axial Rotation	-38	A	-100	B	-77	BC	-62	AC
Left Wrist Flexion	-12	A	-100	B	-15	A	-51	B
Left Wrist Deviation	100	A	82	B	92	AB	69	C
Right Wrist Flexion	-100	AB	-82	A	-64	AB	-87	B
Right Wrist Deviation	87	A	58	AB	100	A	49	B
Torso Side Bending	-30	AC	100	B	-5	C	37	AB
L5S1 Axial Twist	32	A	100	B	49	A	36	A
Left Hip Flexion	100	A	88	B	83	C	94	A
Left Hip Adduction/Abduction	32	A	76	B	100	C	100	C
Left Hip Rotation	-34	A	-81	B	-100	B	-79	B
Right Hip Flexion	100	A	75	B	79	B	94	A
Right Hip Adduction/Abduction	100	A	48	B	82	A	24	C
Right Hip Rotation	53	A	100	B	51	A	20	C
Anterior Carrying Distance	93	A	100	B	87	C	100	B
Lateral Carrying Distance	100	A	-54	B	7	C	48	AC
Lateral Stance Distance	95	A	83	B	100	A	85	B
A/P Stance Distance	10	AB	28	A	-27	B	-100	C

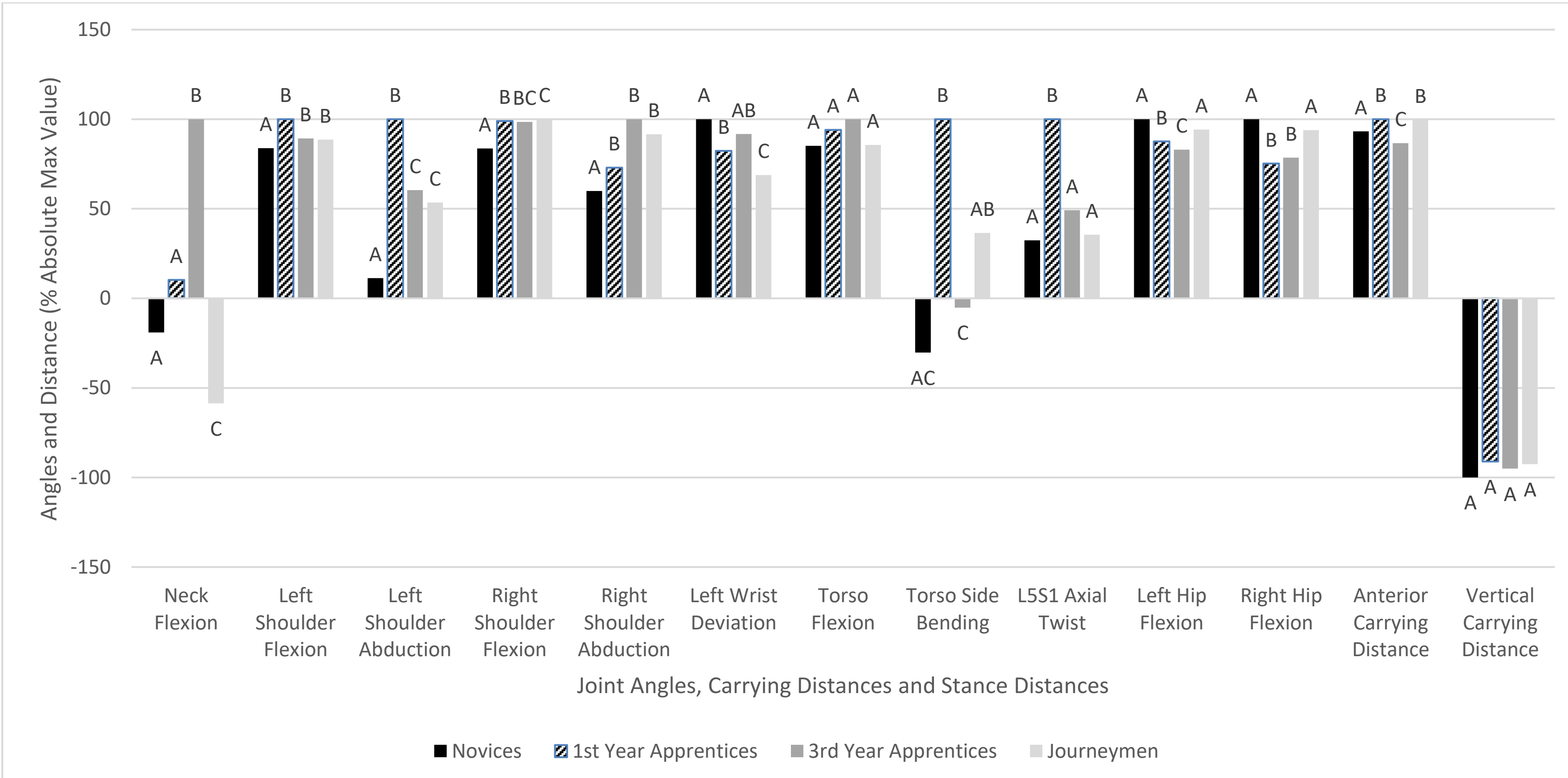


Figure 58: Effect of Experience on Postural Variables at Peak L4/L5 Compression Force

Table 43: Mean Angles (°) and Distance (% Height) of Kinematic Variables at Peak A/P Shear Force

	Novices		**1st Year Apprentices**		**3rd Year Apprentices**		**Journeymen**	
	Mean	*Std dev*	Mean	*Std dev*	Mean	*Std dev*	Mean	*Std dev*
Neck Flexion	1.51	*19.37*	1.33	*21.31*	7.76	*19.23*	-1.97	*16.76*
Neck Side Bending	4.14	*10.58*	-0.37	*10.14*	1.35	*10.56*	-2.95	*13.91*
Left Shoulder Flexion	35.55	*22.28*	44.31	*26.13*	38.56	*29.30*	35.68	*29.76*
Left Shoulder Abduction	4.24	*18.10*	14.77	*18.81*	9.91	*19.31*	11.28	*20.09*
Left Shoulder Axial Rotation	19.09	*40.33*	1.95	*78.99*	18.73	*59.13*	23.32	*47.15*
Right Shoulder Flexion	34.90	*23.75*	39.97	*29.88*	41.88	*29.55*	37.55	*26.55*
Right Shoulder Abduction	10.45	*17.30*	8.30	*20.70*	14.19	*18.06*	11.93	*20.36*
Right Shoulder Axial Rotation	-13.82	*52.02*	-33.01	*64.41*	-19.72	*72.52*	-22.03	*58.76*
Left Wrist Flexion	-6.05	*33.45*	-19.09	*47.31*	-4.86	*32.06*	-10.05	*30.89*
Left Wrist Deviation	16.58	*21.46*	11.89	*28.60*	15.20	*27.38*	11.14	*20.87*
Right Wrist Flexion	-11.01	*35.80*	-12.82	*48.32*	-3.89	*51.60*	-10.43	*30.22*
Right Wrist Deviation	8.93	*25.11*	8.63	*31.05*	10.25	*27.85*	4.52	*21.49*
Torso Flexion	36.02	*31.07*	39.71	*31.38*	41.59	*34.15*	32.86	*31.73*
Torso Side Bending	-7.27	*50.30*	14.71	*53.30*	-4.18	*55.45*	8.00	*48.95*
L5S1 Axial Twist	1.12	*17.62*	7.11	*15.36*	1.53	*16.30*	-0.02	*26.70*
Left Hip Flexion	47.63	*29.19*	43.68	*27.25*	41.61	*31.18*	44.75	*27.88*
Left Hip Adduction/Abduction	1.79	*15.03*	5.60	*13.24*	6.16	*13.72*	8.06	*12.35*
Left Hip Rotation	-7.10	*49.78*	-14.04	*39.36*	-16.57	*34.64*	-18.81	*51.49*
Right Hip Flexion	49.82	*29.85*	39.46	*27.88*	39.39	*29.83*	43.30	*30.36*
Right Hip Adduction/Abduction	11.16	*15.05*	5.61	*11.75*	9.68	*12.91*	2.99	*11.77*
Right Hip Rotation	17.63	*44.78*	25.03	*52.08*	16.83	*38.44*	4.97	*54.97*
Anterior Carrying Distance	19.55	*6.67*	20.36	*7.69*	17.80	*6.91*	19.48	*8.51*
Vertical Carrying Distance	-9.06	*10.77*	-8.63	*10.56*	-8.58	*10.42*	-6.70	*11.90*
Lateral Carrying Distance	1.51	*9.00*	-1.84	*8.88*	-0.39	*10.18*	-0.20	*9.46*
Lateral Stance Distance	17.28	*9.06*	14.98	*8.75*	17.86	*8.47*	16.19	*9.19*
A/P Stance Distance	0.88	*16.24*	2.45	*15.44*	-0.25	*17.83*	-6.45	*14.90*

Table 44: Main Effect of Experience on Mean Kinematic Variables at Peak A/P Shear Force

	Novices		1st Year Apprentices		3rd Year Apprentices		Journeymen	
	Mean (% Absolute Max)	Significance Level	Mean (% Absolute Max)	Significance Level	Mean (% Absolute Max)	Significance Level	Mean (% Absolute Max)	Significance Level
Neck Flexion	20	A	17	B	100	C	-25	D
Neck Side Bending	100	A	-9	B	33	C	-71	D
Left Shoulder Flexion	80	A	100	B	87	BC	81	AC
Left Shoulder Abduction	29	A	100	B	67	C	76	C
Left Shoulder Axial Rotation	82	A	8	B	80	A	100	A
Right Shoulder Flexion	83	A	95	BC	100	C	90	B
Right Shoulder Abduction	74	A	58	A	100	B	84	AB
Right Shoulder Axial Rotation	-42	A	-100	C	-60	AB	-67	B
Left Wrist Flexion	-32	A	-100	B	-25	A	-53	B
Left Wrist Deviation	100	A	72	BC	92	AB	67	C
Right Wrist Flexion	-86	A	-100	AB	-30	B	-81	A
Right Wrist Deviation	87	A	84	A	100	A	44	B
Torso Flexion	87	A	95	B	100	B	79	A
Torso Side Bending	-49	A	100	B	-28	A	54	B
L5S1 Axial Twist	16	A	100	B	22	A	0	A
Left Hip Flexion	100	A	92	AB	87	B	94	A
Left Hip Adduction/Abduction	22	A	70	B	77	B	100	C
Left Hip Rotation	-38	A	-75	AB	-88	BC	-100	C
Right Hip Flexion	100	A	79	BC	79	C	87	AB
Right Hip Adduction/Abduction	100	A	50	B	87	A	27	C
Right Hip Rotation	70	A	100	B	67	A	20	C
Anterior Carrying Distance	96	A	100	B	87	C	96	AB
Vertical Carrying Distance	-100	A	-95	A	-95	A	-74	A
Lateral Carrying Distance	82	A	-100	B	-21	C	-11	AC
Lateral Stance Distance	97	A	84	B	100	A	91	B
A/P Stance Distance	14	AB	38	A	-4	B	-100	C

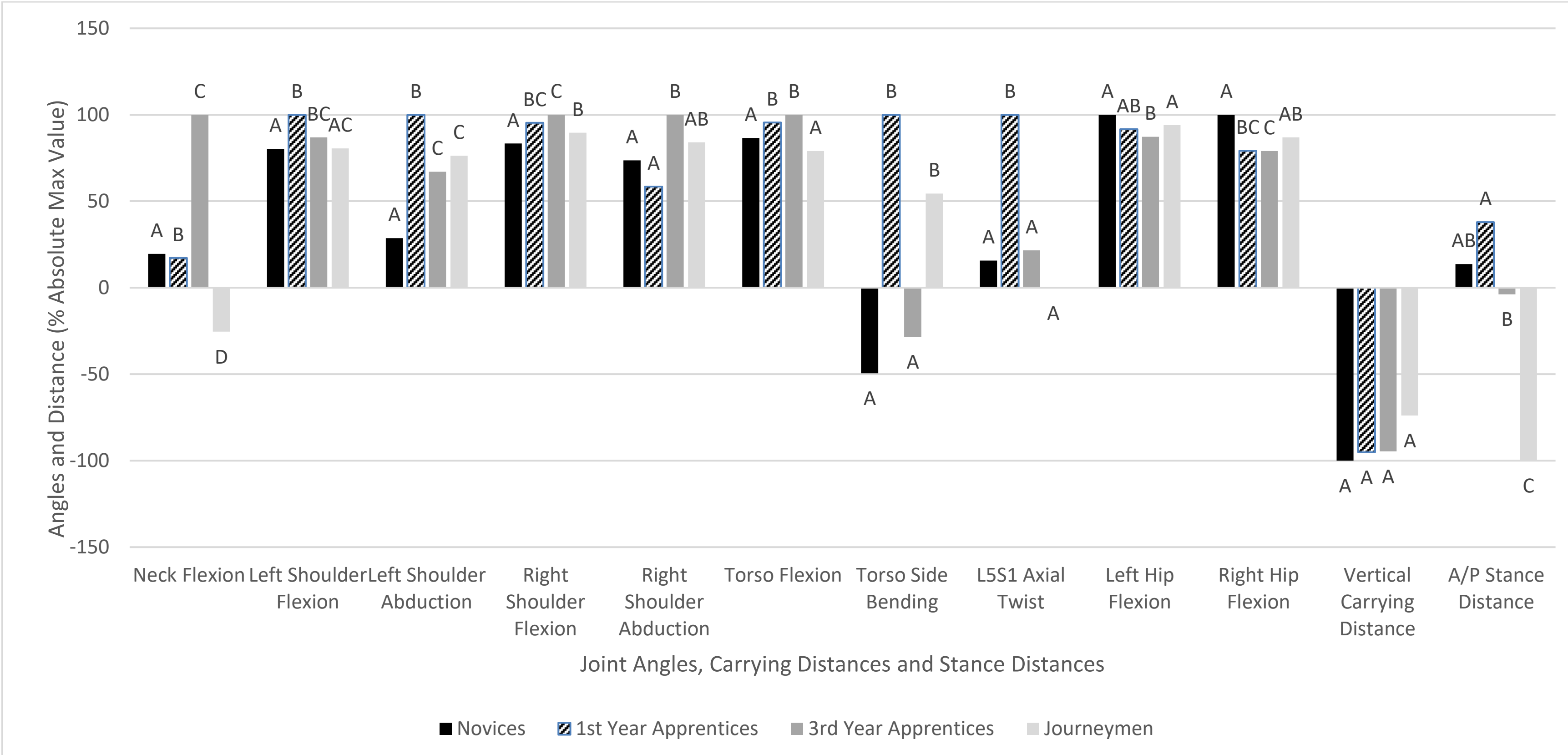


Figure 59: Effect of Experience on Postural Variables at Peak L4/L5 Anterior/Posterior Shear Force

Table 45: Mean Angles (°) and Distance (% Height) of Kinematic Variables at Peak Lateral Shear Force

	Novices		**1st Year Apprentices**		**3rd Year Apprentices**		**Journeymen**	
	Mean	*Std dev*	Mean	*Std dev*	Mean	*Std dev*	Mean	*Std dev*
Neck Flexion	2.35	*17.61*	3.46	*20.66*	9.61	*18.92*	-2.19	*17.26*
Neck Side Bending	4.96	*10.32*	0.04	*9.82*	0.36	*9.97*	-3.79	*14.49*
Left Shoulder Flexion	36.11	*20.12*	41.69	*24.42*	37.18	*25.09*	38.73	*27.16*
Left Shoulder Abduction	2.80	*17.39*	16.00	*18.91*	10.85	*19.63*	8.79	*20.16*
Right Shoulder Flexion	33.85	*21.41*	38.79	*28.13*	41.29	*30.92*	41.39	*26.68*
Right Shoulder Abduction	10.66	*16.79*	10.89	*20.14*	14.96	*16.62*	11.28	*19.31*
Right Shoulder Axial Rotation	-16.57	*48.40*	-32.69	*65.85*	-30.74	*63.90*	-23.37	*59.96*
Right Elbow Flexion	42.91	*24.40*	46.58	*26.01*	48.38	*22.54*	44.36	*23.28*
Left Wrist Flexion	-6.93	*32.89*	-18.52	*43.83*	-6.07	*29.34*	-7.81	*30.98*
Left Wrist Deviation	17.61	*21.11*	14.79	*27.64*	13.34	*26.70*	10.71	*22.59*
Right Wrist Deviation	9.39	*25.11*	7.18	*30.85*	10.24	*27.67*	5.57	*21.01*
Torso Flexion	32.69	*26.07*	33.03	*28.39*	36.39	*30.34*	35.01	*29.11*
Torso Side Bending	-2.55	*45.80*	13.19	*44.28*	3.12	*49.22*	8.09	*48.60*
L5S1 Axial Twist	3.22	*17.74*	8.16	*14.64*	3.20	*16.56*	0.54	*25.69*
Left Hip Flexion	46.89	*27.03*	38.62	*25.53*	37.05	*27.37*	46.88	*25.98*
Left Hip Adduction/Abduction	2.18	*14.40*	5.86	*12.78*	7.41	*12.83*	6.73	*12.68*
Left Hip Rotation	-8.04	*52.62*	-17.60	*40.68*	-19.40	*36.03*	-15.70	*50.73*
Right Hip Flexion	49.38	*26.34*	34.77	*25.24*	36.63	*27.79*	47.20	*27.29*
Right Hip Adduction/Abduction	10.52	*14.93*	5.31	*11.02*	8.99	*11.73*	2.87	*10.81*
Right Hip Rotation	18.96	*43.27*	25.32	*52.05*	16.66	*38.06*	9.32	*59.37*
Left Knee Flexion	22.52	*15.41*	24.79	*13.51*	25.70	*13.93*	24.24	*13.18*
Anterior Carrying Distance	19.92	*6.16*	20.03	*7.10*	18.27	*6.63*	21.12	*7.90*
Vertical Carrying Distance	-8.80	*9.40*	-6.60	*10.18*	-7.27	*9.61*	-8.41	*9.96*
Lateral Carrying Distance	2.54	*8.84*	-0.68	*8.56*	0.15	*9.46*	0.03	*9.92*
Lateral Stance Distance	17.11	*8.74*	15.29	*8.69*	18.28	*8.18*	15.38	*8.70*
A/P Stance Distance	0.84	*16.20*	2.10	*14.32*	-2.03	*16.77*	-4.66	*13.73*

Table 46: Main Effect of Experience on Mean Kinematic Variables at Peak Lateral Shear Force

	Novices		1st Year Apprentices		3rd Year Apprentices		Journeymen	
	Mean (% Absolute Max)	Significance Level	Mean (% Absolute Max)	Significance Level	Mean (% Absolute Max)	Significance Level	Mean (% Absolute Max)	Significance Level
Neck Flexion	24	A	36	A	100	B	-23	C
Neck Side Bending	100	A	1	B	7	B	-76	C
Left Shoulder Flexion	87	A	100	B	89	AB	93	B
Left Shoulder Abduction	17	A	100	B	68	C	55	D
Right Shoulder Flexion	82	A	94	B	100	C	100	C
Right Shoulder Abduction	71	A	73	A	100	B	75	A
Right Shoulder Axial Rotation	-51	A	-100	B	-94	BC	-71	C
Right Elbow Flexion	89	A	96	AB	100	B	92	A
Left Wrist Flexion	-37	A	-100	B	-33	A	-42	A
Left Wrist Deviation	100	A	84	B	76	B	61	C
Right Wrist Deviation	92	A	70	AB	100	A	54	B
Torso Flexion	90	A	91	AB	100	B	96	B
Torso Side Bending	-19	A	100	B	24	A	61	B
L5S1 Axial Twist	39	A	100	B	39	AC	7	C
Left Hip Flexion	100	A	82	B	79	C	100	A
Left Hip Adduction/Abduction	29	A	79	B	100	B	91	B
Left Hip Rotation	-41	A	-91	B	-100	B	-81	B
Right Hip Flexion	100	A	70	B	74	B	96	A
Right Hip Adduction/Abduction	100	A	51	B	85	A	27	C
Right Hip Rotation	75	A	100	B	66	A	37	C
Left Knee Flexion	88	A	96	B	100	B	94	AB
Anterior Carrying Distance	94	A	95	A	87	B	100	C
Vertical Carrying Distance	-100	AC	-75	B	-83	AB	-96	C
Lateral Carrying Distance	100	A	-27	B	6	C	1	C
Lateral Stance Distance	94	A	84	B	100	A	84	B
A/P Stance Distance	18	A	45	A	-44	B	-100	C

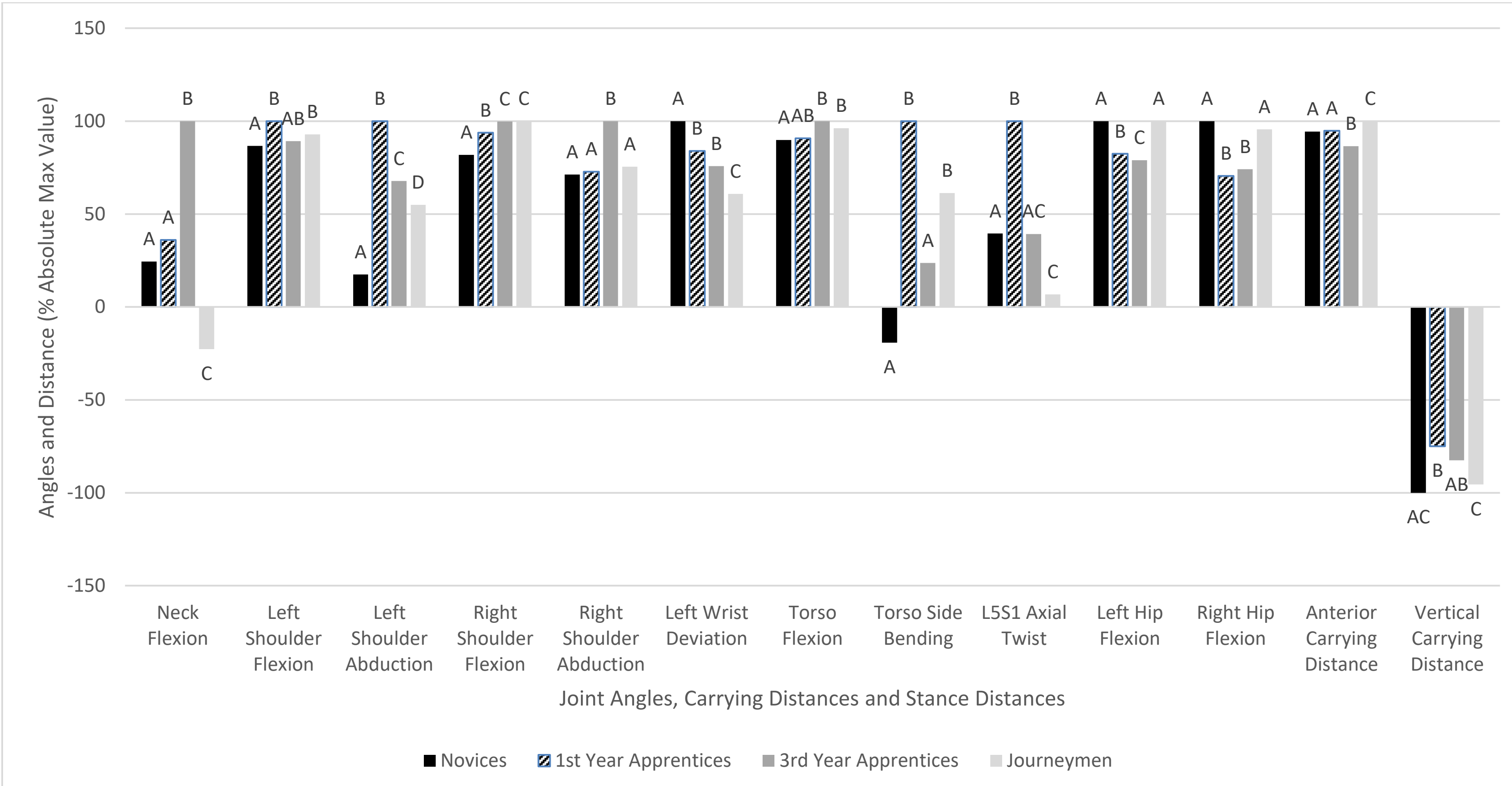


Figure 60: Effect of Experience on Postural Variables at Peak L4/L5 Lateral Shear Force

Table 47: Mean Angles (°) and Distance (% Height) of Kinematic Variables at Peak Left Shoulder Moment

	Novices		**1st Year Apprentices**		**3rd Year Apprentices**		**Journeymen**	
	Mean	*Std dev*	Mean	*Std dev*	Mean	*Std dev*	Mean	*Std dev*
Neck Flexion	-0.70	*17.67*	-0.77	*18.98*	5.38	*17.59*	-5.52	*17.00*
Neck Side Bending	1.69	*10.61*	-0.16	*10.76*	1.94	*9.46*	-3.47	*12.35*
Left Shoulder Flexion	41.14	*20.58*	49.58	*26.61*	41.74	*30.99*	43.91	*26.93*
Left Shoulder Abduction	5.48	*20.18*	16.42	*21.64*	8.37	*19.72*	7.25	*22.42*
Right Shoulder Flexion	35.14	*24.11*	44.23	*32.98*	44.64	*33.02*	41.05	*28.38*
Right Shoulder Abduction	4.79	*16.67*	5.16	*23.49*	13.52	*18.26*	9.66	*18.56*
Right Shoulder Axial Rotation	-14.69	*53.61*	-30.41	*68.81*	-20.46	*70.98*	-22.99	*55.05*
Left Elbow Flexion	37.41	*25.33*	43.71	*26.93*	33.51	*19.95*	37.14	*21.92*
Left Wrist Flexion	0.54	*34.03*	-15.22	*48.49*	-4.83	*27.59*	-8.12	*28.51*
Left Wrist Deviation	15.53	*18.18*	11.39	*29.19*	10.50	*24.57*	8.95	*21.29*
Right Wrist Flexion	-12.21	*36.43*	-9.11	*53.22*	-7.16	*49.86*	-9.70	*31.31*
Right Wrist Deviation	7.70	*25.21*	3.39	*31.73*	6.98	*25.89*	3.71	*20.76*
Torso Flexion	34.15	*30.48*	41.41	*40.04*	44.63	*38.23*	35.56	*32.10*
Torso Side Bending	0.61	*50.15*	16.89	*60.11*	-1.21	*62.86*	14.32	*50.87*
L5S1 Axial Twist	3.07	*17.81*	8.00	*16.71*	3.87	*19.35*	4.38	*26.60*
Left Hip Flexion	48.10	*31.97*	42.48	*30.45*	42.25	*32.84*	46.11	*28.21*
Left Hip Adduction/Abduction	2.07	*14.33*	6.60	*13.43*	7.37	*14.10*	9.46	*12.83*
Left Hip Rotation	-6.46	*46.33*	-10.54	*35.89*	-17.51	*33.48*	-18.00	*44.15*
Right Hip Flexion	50.08	*32.07*	36.96	*30.83*	41.87	*32.73*	46.59	*31.17*
Right Hip Adduction/Abduction	10.53	*16.18*	4.99	*11.48*	8.36	*13.12*	1.48	*11.81*
Right Hip Rotation	16.27	*42.94*	28.90	*56.78*	10.89	*35.03*	-2.64	*52.23*
Left Knee Flexion	25.67	*19.77*	27.30	*14.47*	27.02	*15.77*	25.45	*12.47*
Anterior Carrying Distance	19.37	*7.26*	20.85	*8.14*	17.62	*8.64*	20.39	*9.13*
Vertical Carrying Distance	-9.63	*10.13*	-8.61	*11.73*	-10.64	*9.38*	-9.09	*10.38*
Lateral Carrying Distance	0.63	*11.14*	-2.04	*10.43*	0.44	*11.67*	1.62	*12.09*
Lateral Stance Distance	16.95	*8.74*	15.38	*9.24*	18.05	*8.82*	16.17	*9.40*
A/P Stance Distance	0.69	*16.53*	2.70	*15.60*	-1.30	*18.62*	-6.91	*16.37*

Table 48: Main Effect of Experience on Mean Kinematic Variables at Peak Left Shoulder Moment

	Novices		1st Year Apprentices		3rd Year Apprentices		Journeymen	
	Mean (% Absolute Max)	Significance Level	Mean (% Absolute Max)	Significance Level	Mean (% Absolute Max)	Significance Level	Mean (% Absolute Max)	Significance Level
Neck Flexion	-13	B	-14	B	98	A	-100	C
Neck Side Bending	49	AB	-5	B	56	A	-100	C
Left Shoulder Flexion	83	C	100	A	84	BC	89	AB
Left Shoulder Abduction	33	B	100	A	51	B	44	B
Right Shoulder Flexion	79	A	99	B	100	B	92	B
Right Shoulder Abduction	35	A	38	B	100	C	71	B
Right Shoulder Axial Rotation	-48	A	-100	C	-67	AB	-76	B
Left Elbow Flexion	86	B	100	A	77	C	85	BC
Left Wrist Flexion	4	A	-100	C	-32	B	-53	BC
Left Wrist Deviation	100	A	73	AB	68	BC	58	C
Right Wrist Flexion	-100	B	-75	A	-59	AB	-79	B
Right Wrist Deviation	100	A	44	AB	91	A	48	B
Torso Flexion	77	C	93	B	100	A	80	BC
Torso Side Bending	4	B	100	A	-7	B	85	A
L5S1 Axial Twist	38	A	100	B	48	A	55	A
Left Hip Flexion	100	AB	88	BC	88	C	96	A
Left Hip Adduction/Abduction	22	A	70	B	78	B	100	C
Left Hip Rotation	-36	A	-59	A	-97	B	-100	B
Right Hip Flexion	100	A	74	B	84	B	93	A
Right Hip Adduction/Abduction	100	A	47	B	79	A	14	C
Right Hip Rotation	56	A	100	B	38	A	-9	C
Left Knee Flexion	94	C	100	A	99	AB	93	BC
Anterior Carrying Distance	93	A	100	B	84	C	98	B
Vertical Carrying Distance	-90	A	-81	A	-100	B	-85	AB
Lateral Carrying Distance	31	A	-100	B	22	A	79	C
Lateral Stance Distance	94	A	85	B	100	A	90	B
A/P Stance Distance	10	A	39	A	-19	B	-100	C

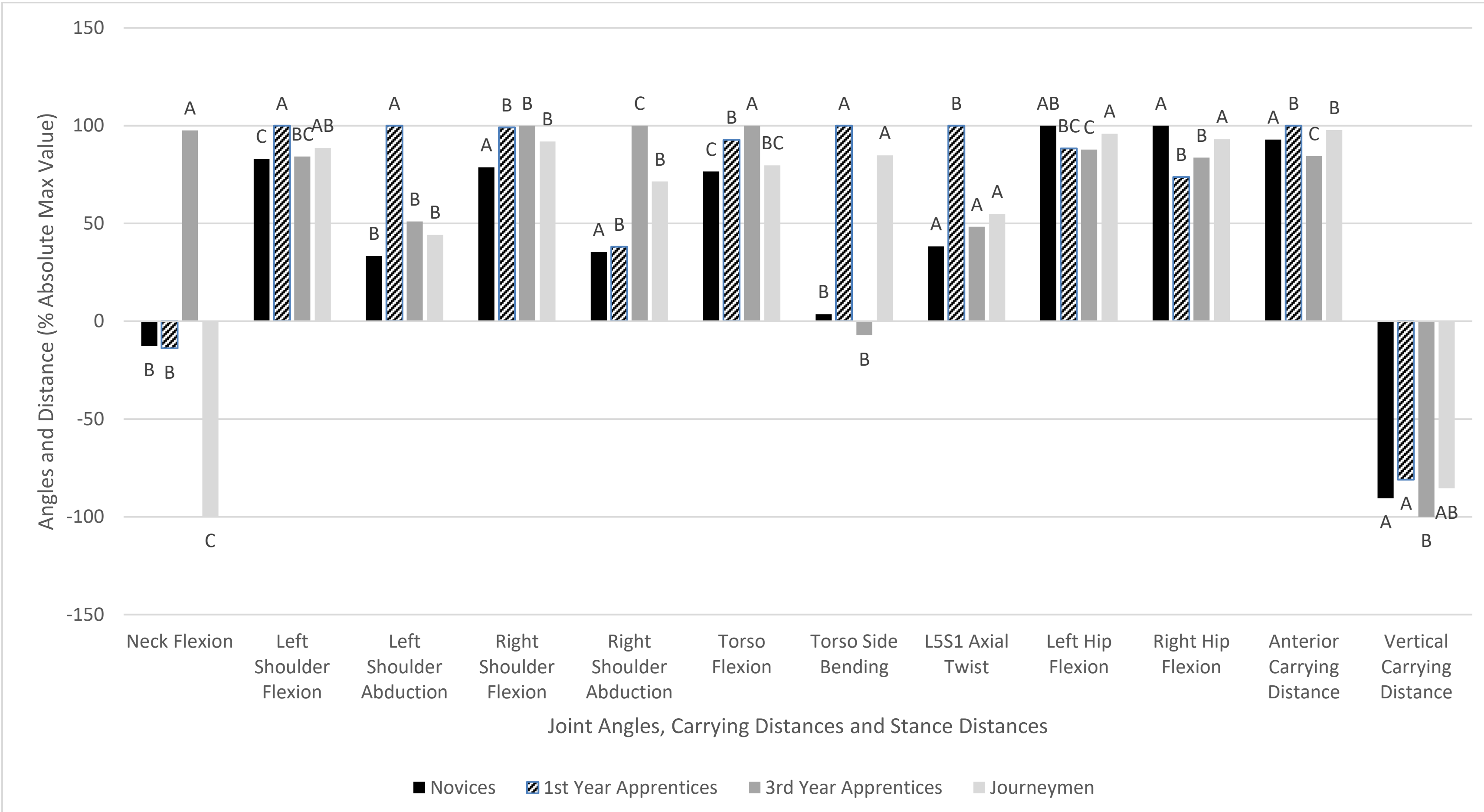


Figure 61: Effect of Experience on Postural Variables at Peak Left Shoulder Moment

Table 49: Mean Angles (°) and Distance (% Height) of Kinematic Variables at Peak Right Shoulder Moment

	Novices		**1st Year Apprentices**		**3rd Year Apprentices**		**Journeymen**	
	Mean	*Std dev*	Mean	*Std dev*	Mean	*Std dev*	Mean	*Std dev*
Neck Flexion	-0.47	*19.35*	0.49	*17.51*	6.37	*17.72*	-4.83	*17.04*
Neck Side Bending	3.11	*10.73*	0.56	*11.19*	1.34	*10.01*	-2.74	*14.63*
Left Shoulder Abduction	2.76	*18.40*	9.18	*16.43*	7.69	*19.11*	5.47	*21.80*
Right Shoulder Flexion	39.71	*22.18*	42.42	*27.45*	44.57	*30.91*	46.73	*27.15*
Right Shoulder Abduction	6.81	*18.90*	2.98	*21.63*	12.96	*18.38*	12.53	*20.01*
Right Shoulder Axial Rotation	-9.00	*56.55*	-14.65	*70.78*	-19.33	*73.38*	-16.57	*62.35*
Right Elbow Flexion	36.83	*23.57*	38.31	*23.29*	39.55	*23.54*	37.83	*22.59*
Left Wrist Flexion	-1.43	*33.01*	-17.02	*45.93*	-4.69	*28.78*	-8.25	*29.26*
Left Wrist Deviation	12.06	*21.19*	12.10	*26.90*	10.16	*25.02*	9.42	*20.44*
Right Wrist Deviation	7.00	*25.46*	4.90	*30.72*	6.50	*27.02*	3.58	*20.18*
Torso Flexion	36.89	*32.56*	38.53	*37.60*	41.40	*37.88*	36.41	*31.79*
Torso Side Bending	-11.34	*51.23*	3.82	*59.14*	-11.41	*58.35*	0.21	*53.39*
Left Hip Flexion	48.74	*32.22*	40.58	*29.06*	39.80	*32.94*	44.79	*27.17*
Left Hip Adduction/Abduction	-0.45	*13.72*	4.07	*13.01*	6.21	*13.36*	7.54	*12.62*
Left Hip Rotation	-3.54	*47.86*	-11.66	*41.38*	-17.38	*36.21*	-17.00	*49.24*
Right Hip Flexion	52.16	*32.25*	34.96	*30.60*	39.03	*33.32*	48.47	*30.60*
Right Hip Adduction/Abduction	12.45	*15.91*	6.91	*11.03*	9.51	*12.57*	3.66	*11.06*
Right Hip Rotation	15.03	*38.72*	25.47	*58.24*	14.72	*38.25*	0.12	*49.09*
Right Knee Flexion	27.44	*18.56*	24.40	*14.32*	24.41	*15.49*	24.22	*12.40*
Anterior Carrying Distance	19.63	*7.48*	18.23	*9.07*	16.53	*8.73*	19.09	*8.22*
Vertical Carrying Distance	-10.40	*9.57*	-7.54	*10.82*	-9.32	*9.85*	-9.10	*10.44*
Lateral Carrying Distance	1.23	*10.93*	-2.37	*9.96*	0.12	*11.05*	2.06	*12.89*
Lateral Stance Distance	16.51	*8.72*	15.42	*9.16*	18.24	*8.65*	16.67	*8.71*
A/P Stance Distance	-0.37	*16.90*	1.65	*15.54*	-1.57	*18.37*	-8.38	*15.39*

Table 50: Main Effect of Experience on Mean Kinematic Variables at Peak Right Shoulder Moment

	Novices		1st Year Apprentices		3rd Year Apprentices		Journeymen	
	Mean (% Absolute Max)	Significance Level	Mean (% Absolute Max)	Significance Level	Mean (% Absolute Max)	Significance Level	Mean (% Absolute Max)	Significance Level
Neck Flexion	-7	A	8	A	100	B	-76	C
Neck Side Bending	100	A	18	B	43	AB	-88	C
Left Shoulder Abduction	30	C	100	A	84	B	60	C
Right Shoulder Flexion	85	C	91	B	95	A	100	A
Right Shoulder Abduction	53	A	23	A	100	B	97	B
Right Shoulder Axial Rotation	-47	A	-76	AB	-100	B	-86	AB
Right Elbow Flexion	93	B	97	AB	100	A	96	AB
Left Wrist Flexion	-8	A	-100	C	-28	AB	-48	B
Left Wrist Deviation	100	AB	100	A	84	BC	78	C
Right Wrist Deviation	100	A	70	A	93	A	51	B
Torso Flexion	89	B	93	AB	100	A	88	AB
Torso Side Bending	-99	B	33	A	-100	B	2	A
Left Hip Flexion	100	A	83	B	82	B	92	A
Left Hip Adduction/Abduction	-6	A	54	B	82	C	100	D
Left Hip Rotation	-20	A	-67	B	-100	C	-98	C
Right Hip Flexion	100	A	67	B	75	B	93	A
Right Hip Adduction/Abduction	100	A	55	B	76	C	29	D
Right Hip Rotation	59	B	100	A	58	B	0	C
Right Knee Flexion	100	A	89	B	89	B	88	B
Anterior Carrying Distance	100	AB	93	B	84	C	97	A
Vertical Carrying Distance	-100	A	-72	B	-90	A	-88	A
Lateral Carrying Distance	52	A	-100	B	5	A	87	C
Lateral Stance Distance	90	B	85	C	100	A	91	BC
A/P Stance Distance	-4	AB	20	A	-19	B	-100	C

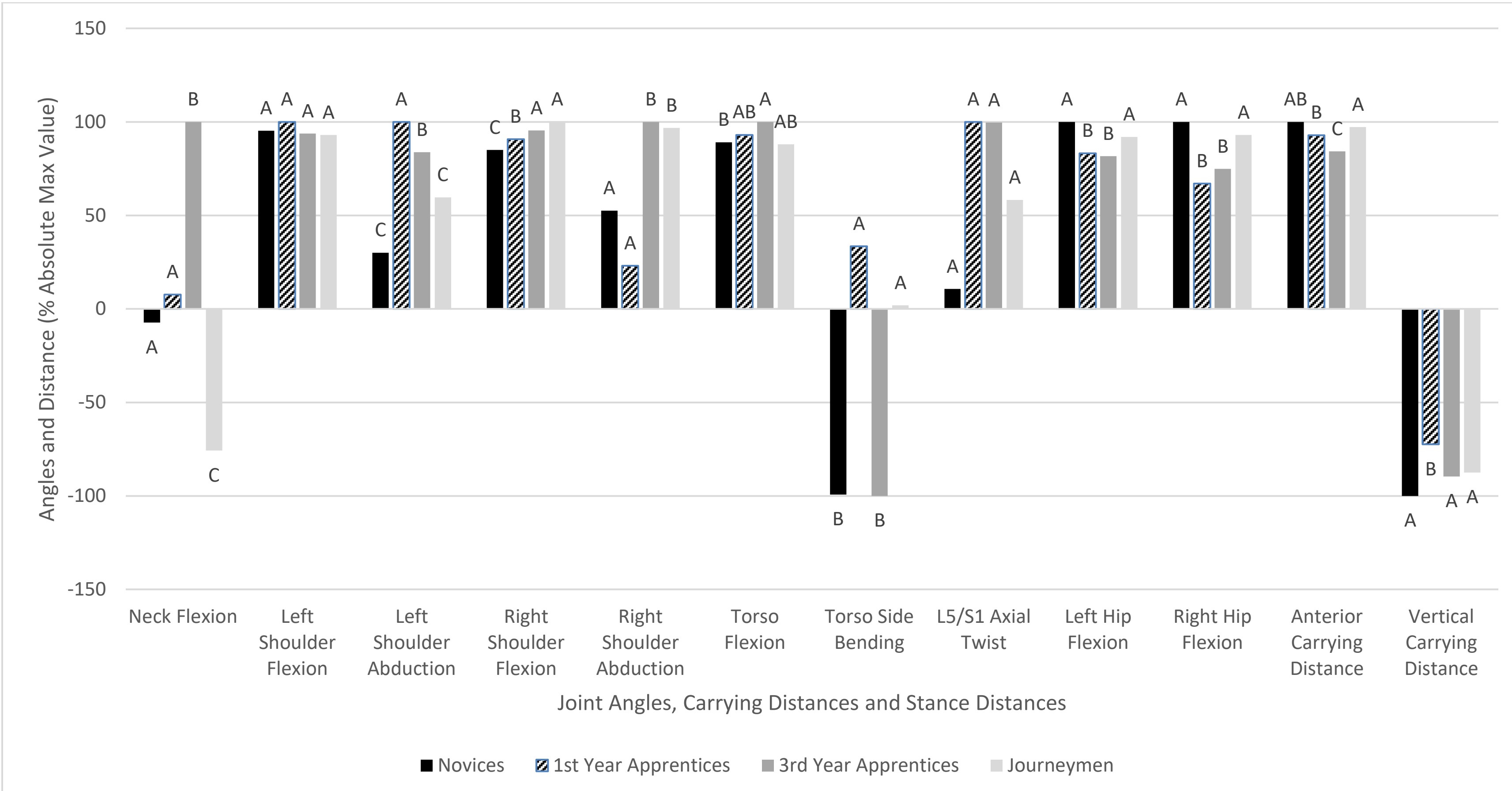


Figure 62: Effect of Experience on Postural Variables at Peak Right Shoulder Moment

Appendix F
Enhanced Training Tool Design Mock-Ups

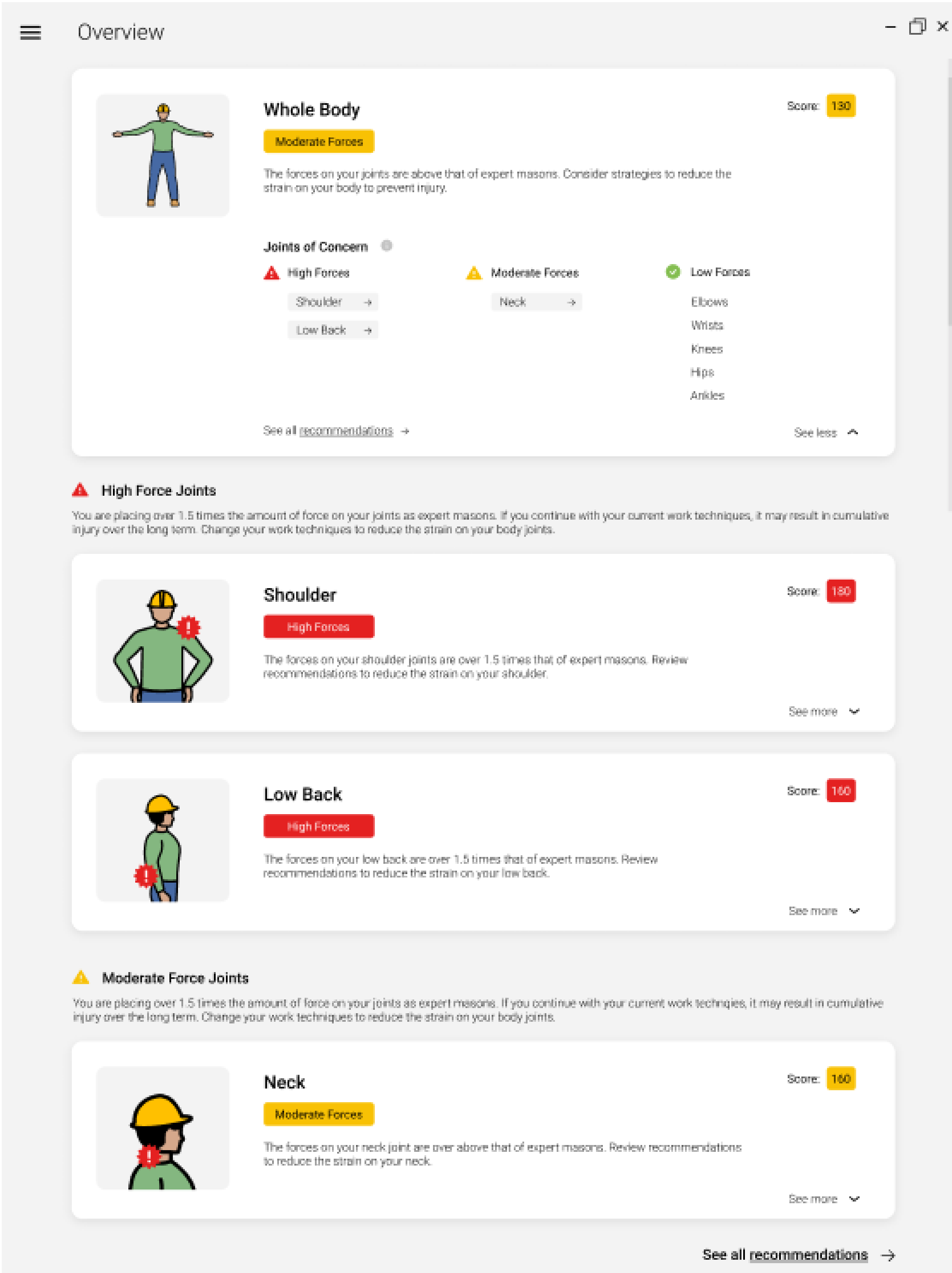


Figure 63: Overview Dashboard

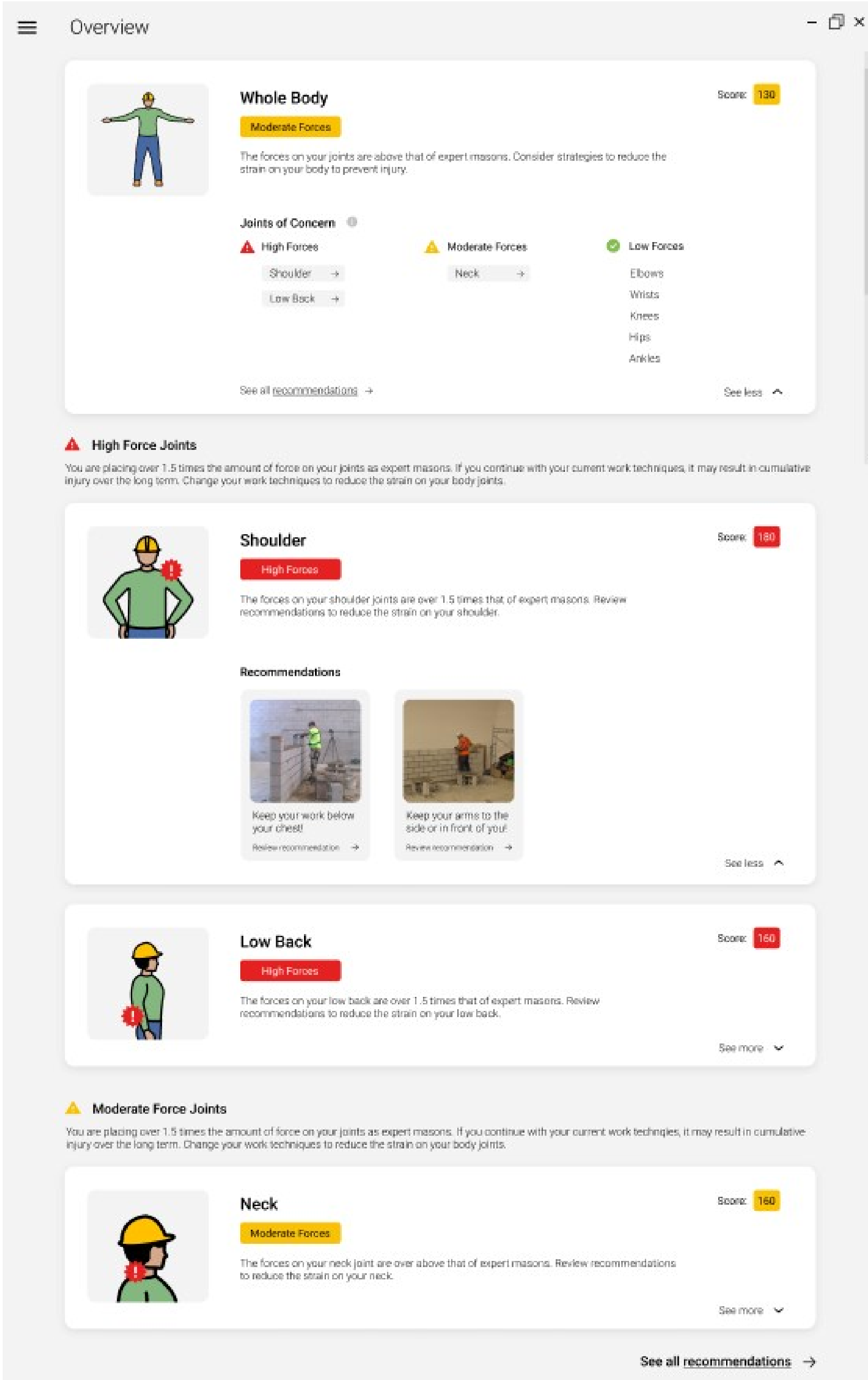


Figure 64: Overview Dashboard with Expanded Information for the Shoulder

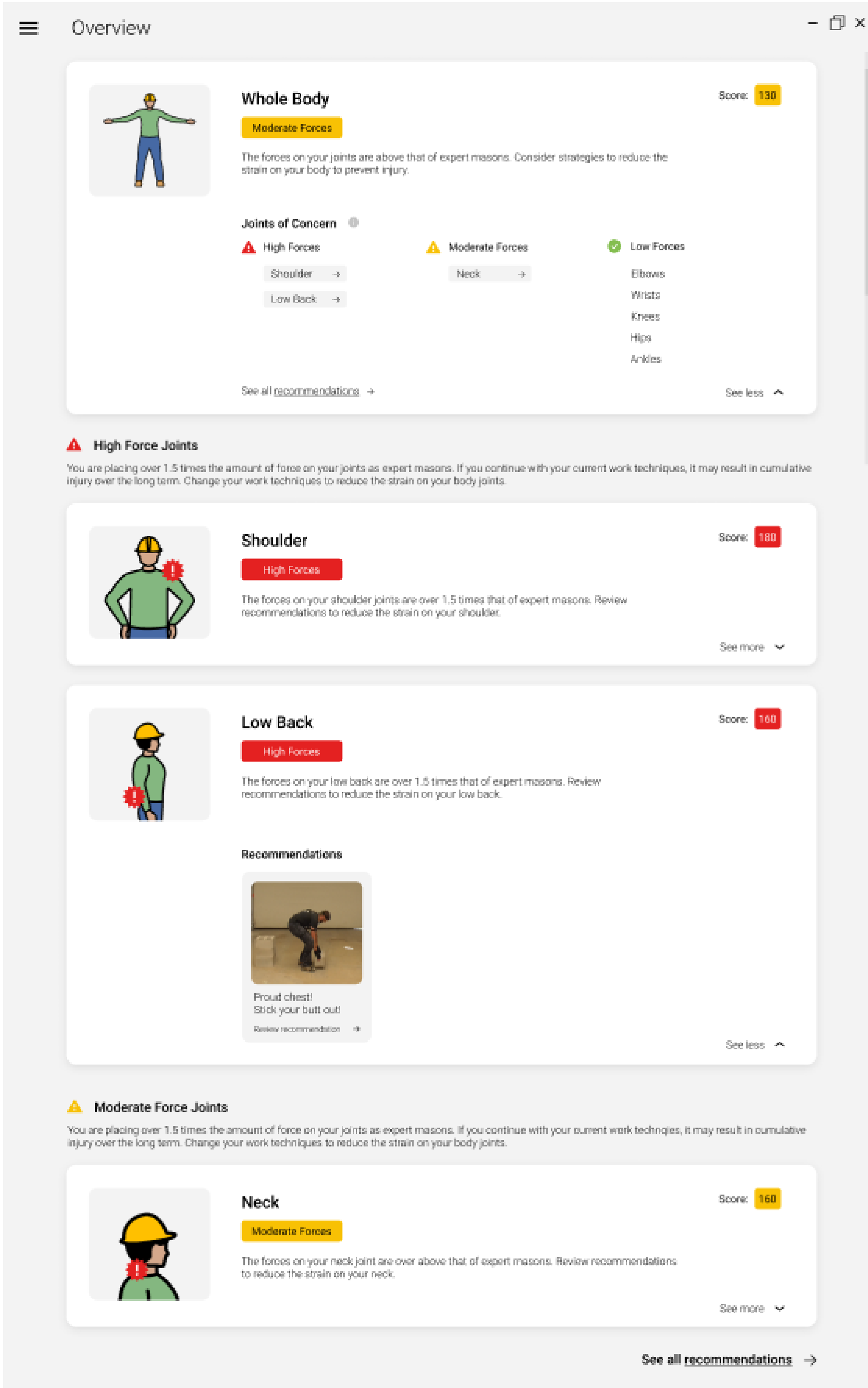


Figure 65: Overview Dashboard with Expanded Information for the Low Back

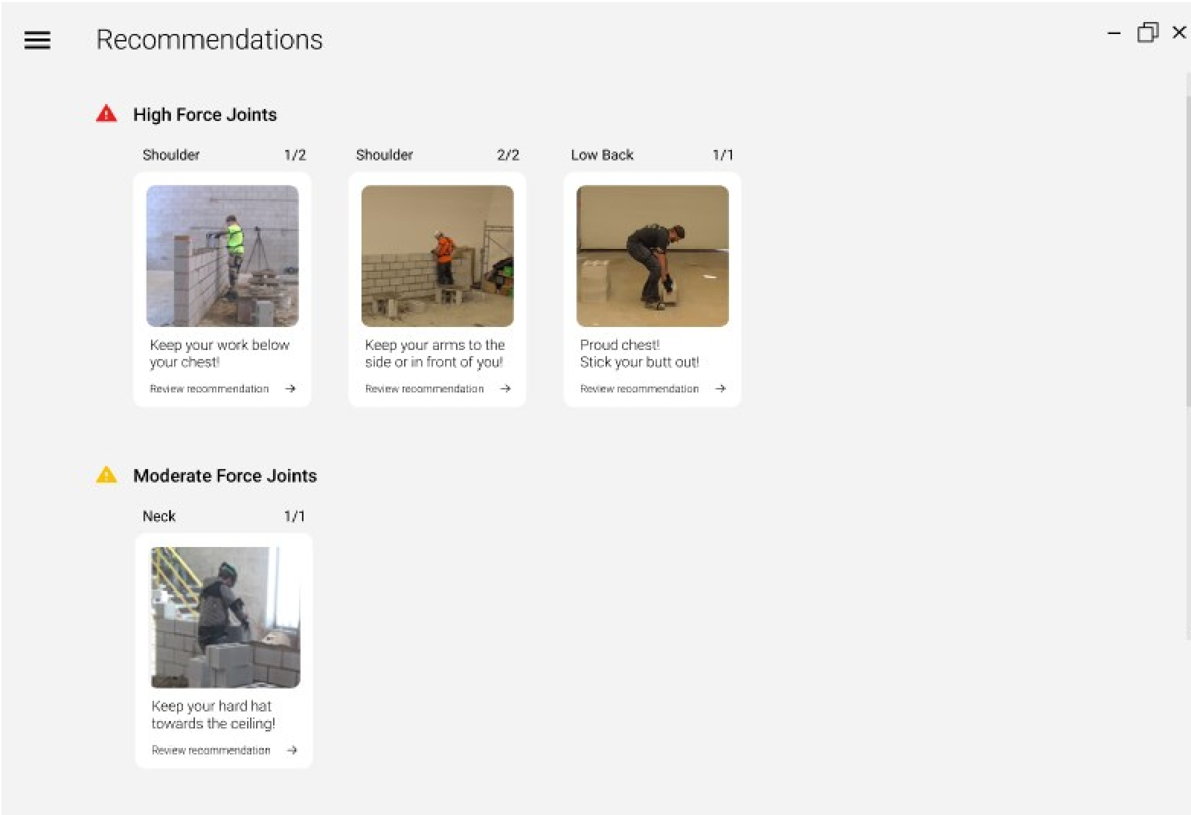


Figure 66: Recommendations Dashboard

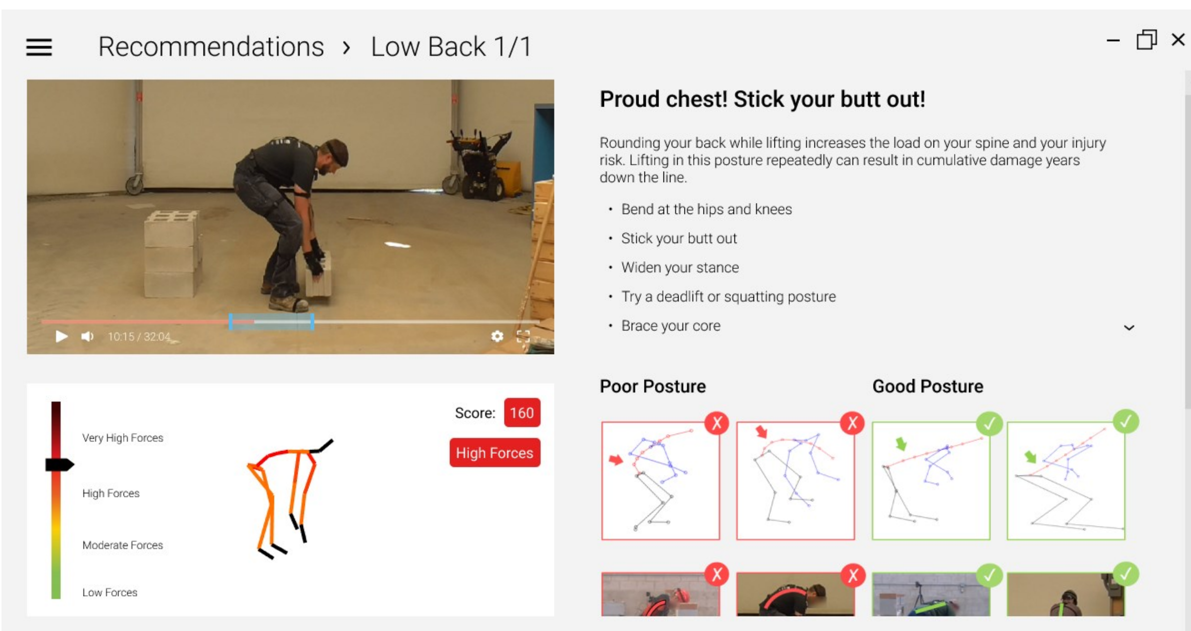


Figure 67: Recommendations for the Low Back

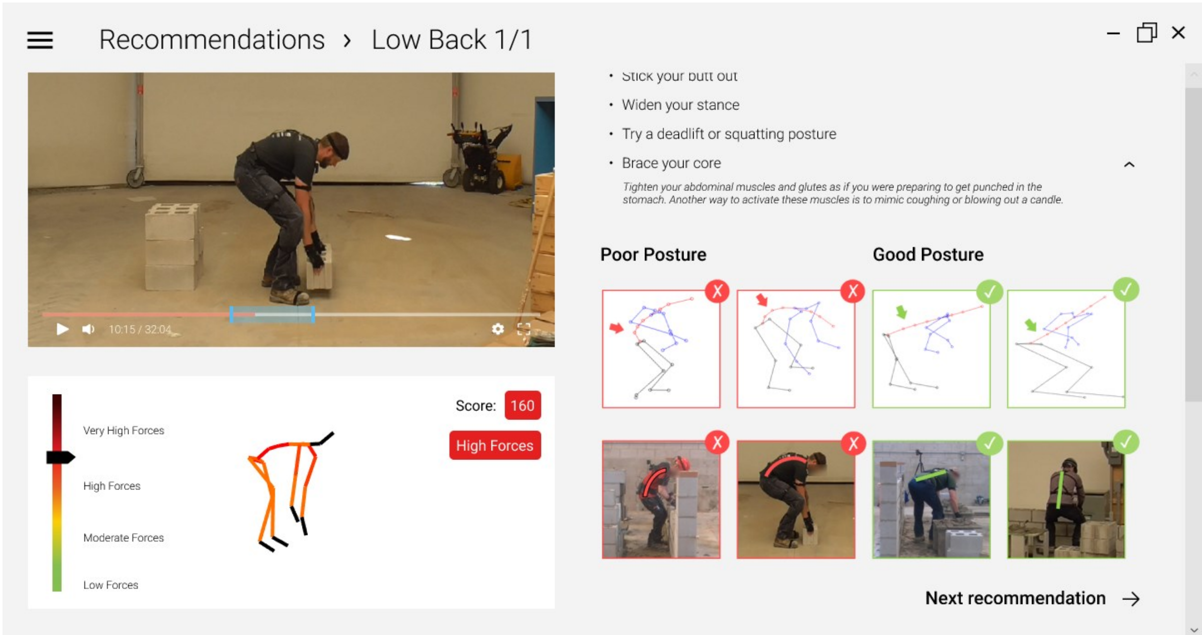


Figure 68: Recommendations for the Low Back with View of Images and Expanded Information

Appendix G
Educational Training Module for Muscle Injury Prevention in Masonry

The following figures are the slides from the educational training module developed for instructor use in the classroom. Each of the slides have additional teaching information in the notes to supplement the slide, not included in this Appendix.

COURSE OUTLINE

1. Muscle Injuries in Masonry
2. Preventing Muscle Injury
3. Warming Up Before Work
4. Safe Lifting Techniques
5. Motion-Based Training Tool

MUSCLE INJURIES IN MASONRY

What are they & why should I care?

MODULE OBJECTIVES

1. Explain what muscle injuries are
2. Understand the impacts of muscle injuries
3. Recognize symptoms of muscle injuries
4. Learn what to do if you have symptoms
5. Be aware of employer responsibilities

Do you know anyone who has gotten a muscle injury at work?

WHAT ARE MUSCLE INJURIES?

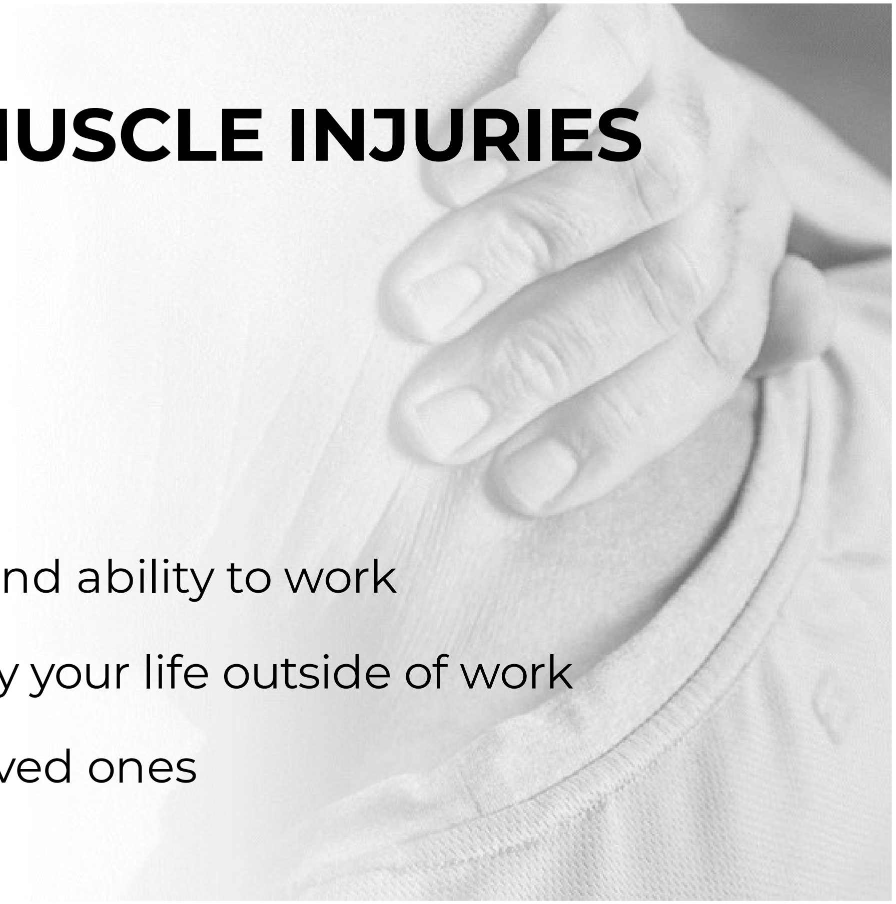
- Injuries of the soft tissues in the body
- Muscle injuries can happen suddenly or gradually
- Examples:
  - Back pain
  - Carpal tunnel
  - Tendonitis (e.g., tennis elbow)
  - Sprains and strains

PREVALENCE OF MUSCLE INJURIES

- Most **common** workplace injury
- **40%** of all WSIB lost -time injuries in Ontario
- **1 in every 10** Canadian adults have had a muscle injury
- **50% higher risk** in construction

Source: MOL; PSHSA; Schneider, 2001

IMPACTS OF MUSCLE INJURIES



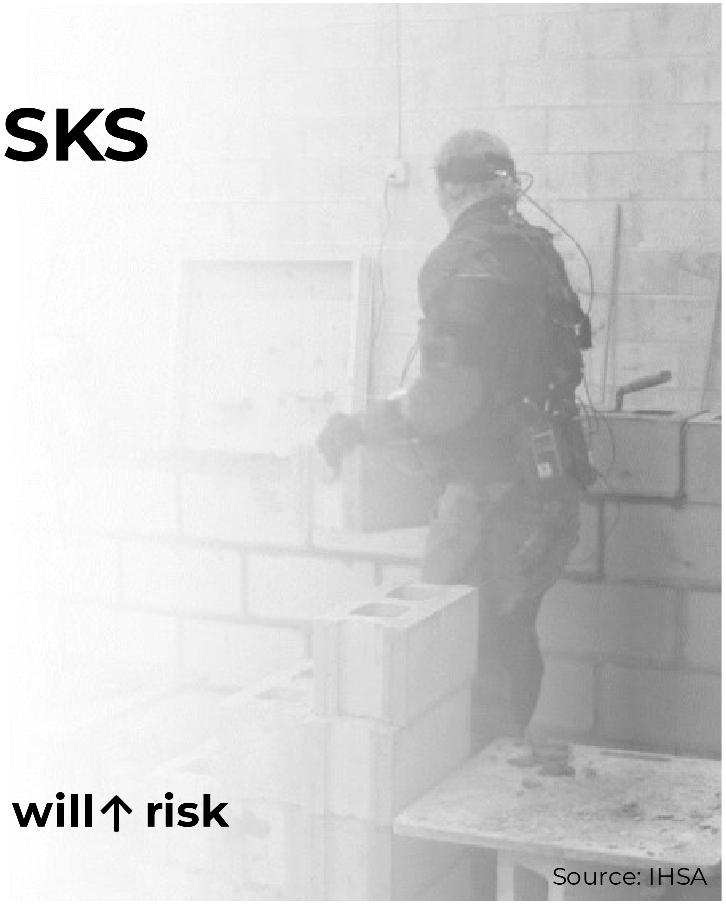
- Pain & suffering
- Damages your health
- Medical expenses
- Reduces productivity and ability to work
- Reduces ability to enjoy your life outside of work
- Affects your family & loved ones

MUSCLE INJURY RISKS

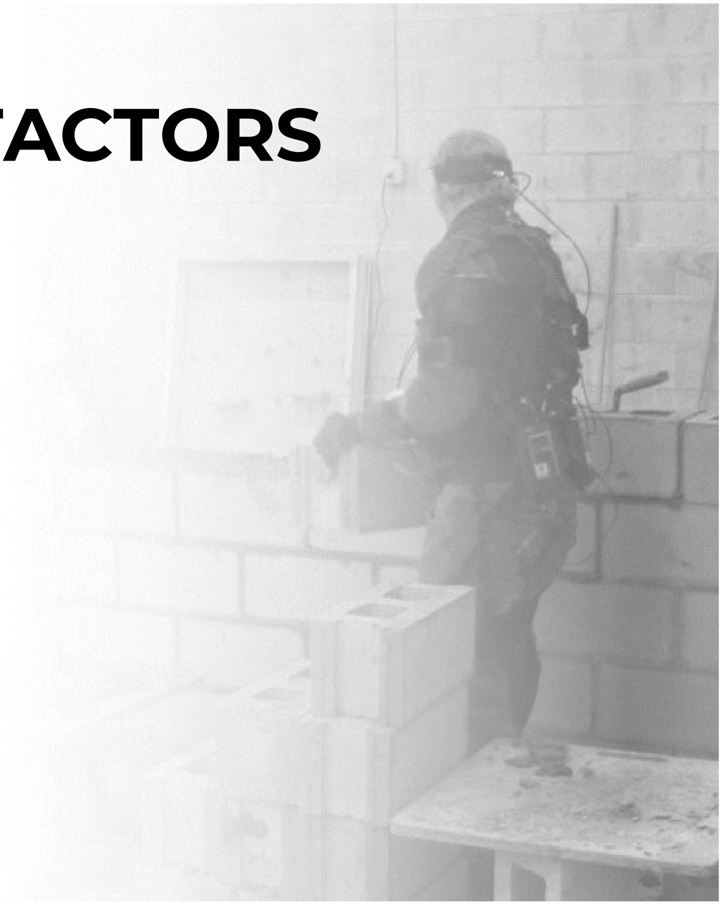
- Forces
- Awkward postures
- Repetition

- Other
  - Contact stress
  - Vibration
  - Extreme temperatures

- **Any combination of the above will ↑ risk**

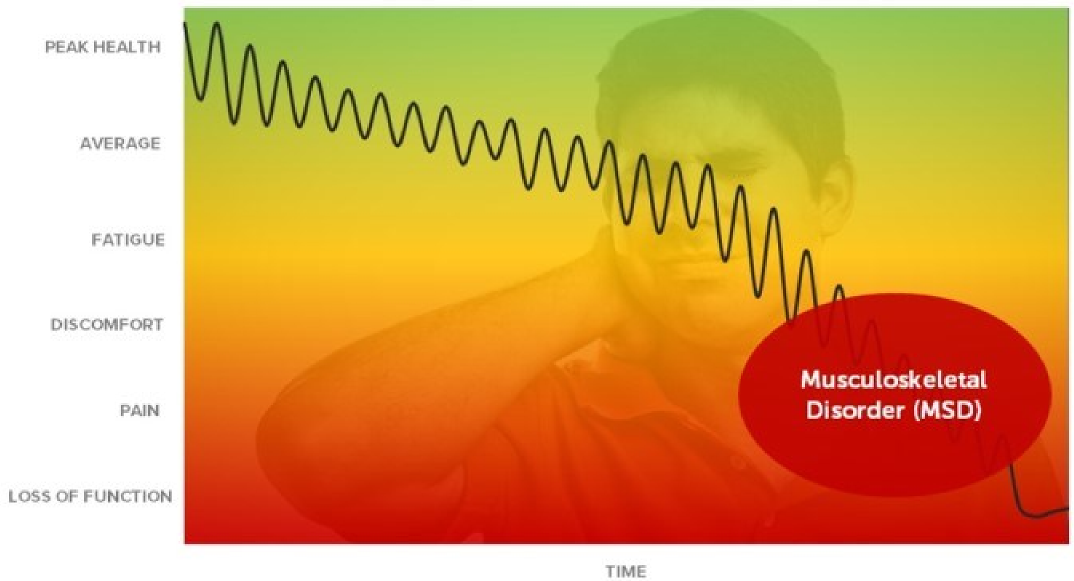


INDIVIDUAL RISK FACTORS



- Situational risk factors
- Poor work habits
- Poor health or fitness
- Lack of rest and recovery
- Age

MUSCLE INJURIES



Source: ErgoPlus
Educational use only

MUSCLE INJURY SYMPTOMS

- Pain
- Discomfort
- Aching
- Swelling
- Tingling
- Numbness
- Burning
- Weakness
- Stiff joints
- Reduced range of motion
- Interferes with daily activities

MUSCLE INJURY SYMPTOMS

- **Early:** Aching and tiredness during the work shift that disappear at night and during days off
- **Intermediate:** Aching and tiredness early in the work shift and continue at night. Affects ability to do repetitive work.
- **Late:** Aching, fatigue, and weakness persist at rest. Inability to sleep and to perform light duties.

Source: CCOHS

ONCE SYMPTOMS APPEAR

- Start treatments and interventions early
- See a healthcare practitioner
- Identify any contributing factors
  - Can you make changes to the workplace?
  - Equipment?
  - Work methods?

EMPLOYER RESPONSIBILITIES

- Keep equipment in good condition
- Provide information, instruction and supervision
- Communicate hazards
- Take every precaution reasonable in the circumstances
- Monthly inspection (if > 5 workers)
- Review and comply with applicable regulations

Source: Ontario Government Website

PREVENTING MUSCLE INJURY

So, what can I do about it?

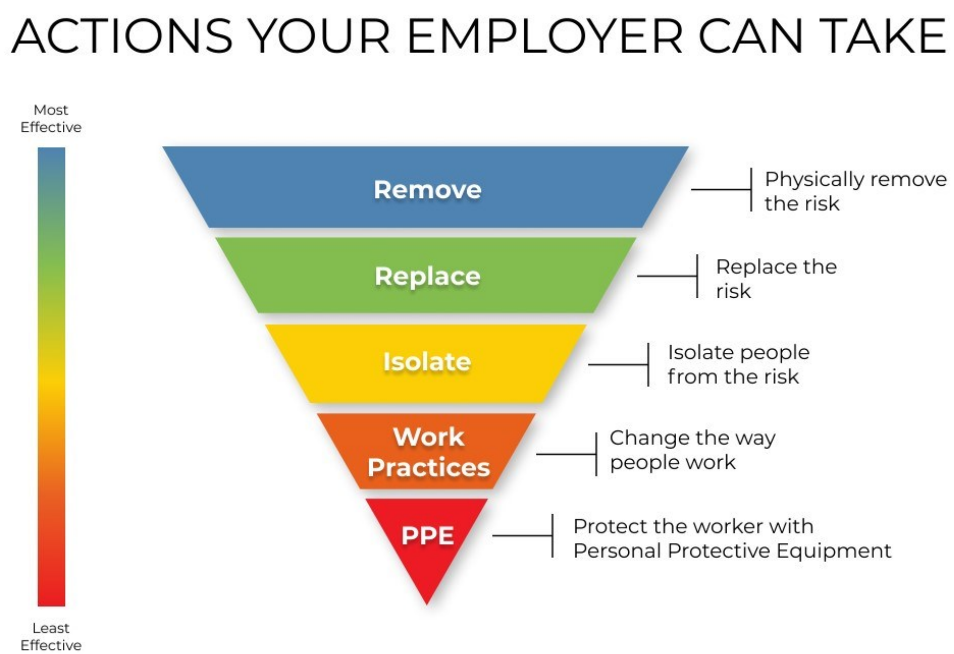
MODULE OBJECTIVES

1. Understand the different types of interventions
2. Think critically about how to reduce risk
3. Provide examples of interventions in masonry

What factors affect how risky a lifting task is?

How might we reduce the risk for a lifting task?

PREVENTING INJURIES



Based on NISOH, 2015

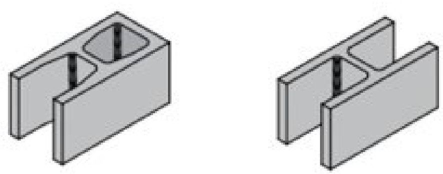
EXAMPLES IN MASONRY

- Equipment
  - Self-leveling pallet
  - Mortar silo
  - Grout delivery systems
  - Adjustable scaffolding

Source: Hess et al., 2010; Ryu et al., 2020

EXAMPLES IN MASONRY

- Materials
  - Light weight block
  - H-block & A-blocks



Open end, or "A" shaped unit

Double open end unit

Source: Hess et al., 2010

EXAMPLES IN MASONRY

- Work Practices
  - Half-size pallets
  - Half-weight cement bags
  - Two-person lift teams for large blocks

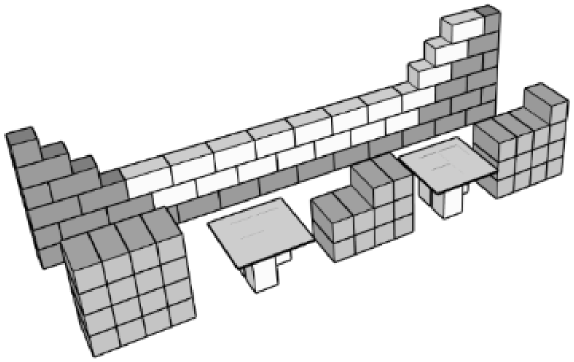
Source: Hess et al., 2010

TROWELS

- Bigger isn't always better
- Certain brands may put more pressure on wrist
- Choose one that's right for you

WORK LAYOUT

- Set up materials close to work
- Avoid awkward postures or reaching
- Avoid obstructing working area



WORK PRACTICES

- Warming up before work
- Lift training
- **Focus of the 2nd half of this course**

WARMING UP BEFORE WORK

What's the big deal anyways?

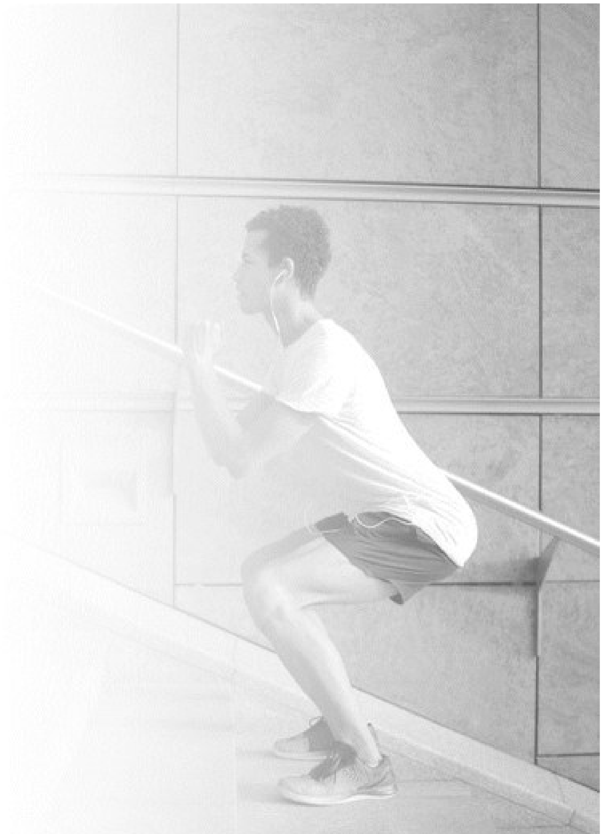
MODULE OBJECTIVES

1. Understand why warming up is important
2. Learn how to warm -up
3. Learn the role of stretching

How do you prevent injury before playing sports or doing a workout?

WHY WARM UP

- **Prevent injury**
- ↑ blood flow to the muscle
- ↑ range of motion and flexibility
- ↑ balance and posture
- ↑ performance
- ↓ muscle tension and pain
- ↓ muscle soreness after work



Source: Sports Medicine, 2009; Fradkin et al., 2006; Manson Construction Co, 2014; Cronkleton & Bubnis (Healthline), 2019

WARMING UP

- Before work you should focus on **movement**
- Actively move through your range of motion to increase your heart rate & get warm
- Do **not** hold one position for a long period of time
- If muscles are tight, you can do traditional stretches **after** work

Source: Cronkleton & Bubnis (Healthline), 2019

Get moving before work, **stretch** after work

WARM UP EXERCISES

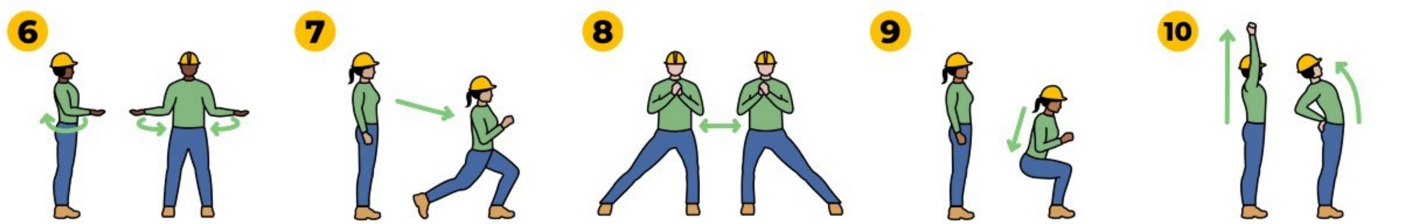
Half Jacks — Repeat for 20s

High Knees — Repeat for 20s

Butt Kicks — Repeat for 20s

Arm Circles — 10x Forwards & Backwards

Arm Swings — Repeat 10x



No Money — Repeat 10x

Lunges — 5x Each Side

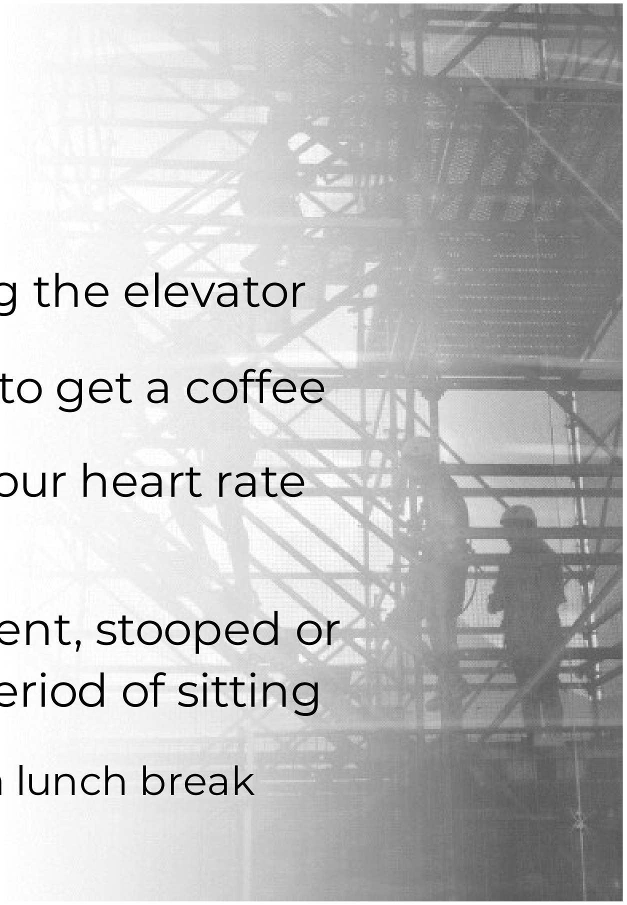
Side Lunges — 5x Each Side

Squats — Repeat 10x

Back Extension — Repeat 3x

5 minutes is all it takes for prevention

DON'T HAVE TIME?



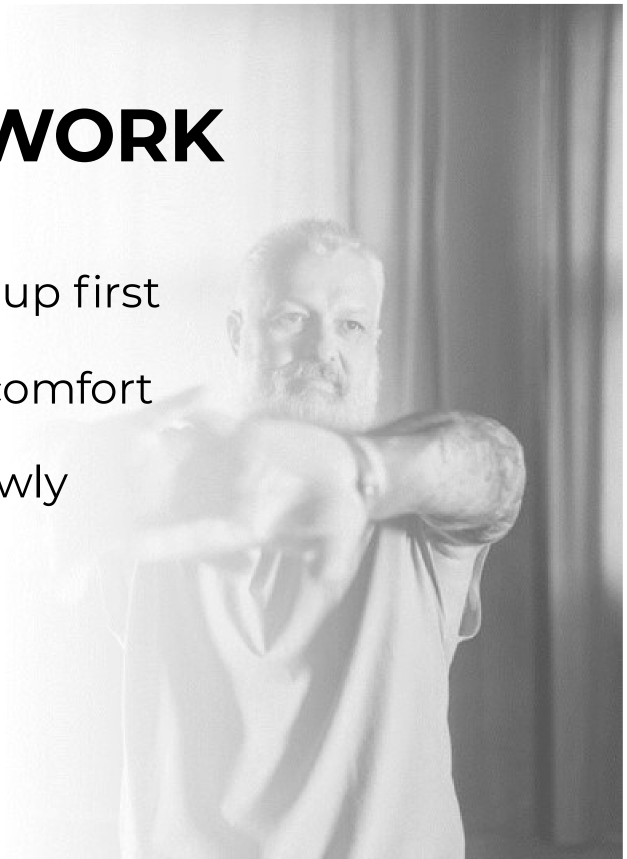
- Walk up the stairs instead of taking the elevator
- A brisk walk around the job site or to get a coffee
- Jog in place for a minute to raise your heart rate

- 1-3 Back extensions working in a bent, stooped or crouched posture or after a long period of sitting
  - E.g., after your commute to work or a lunch break

Get moving before work,
stretch after work

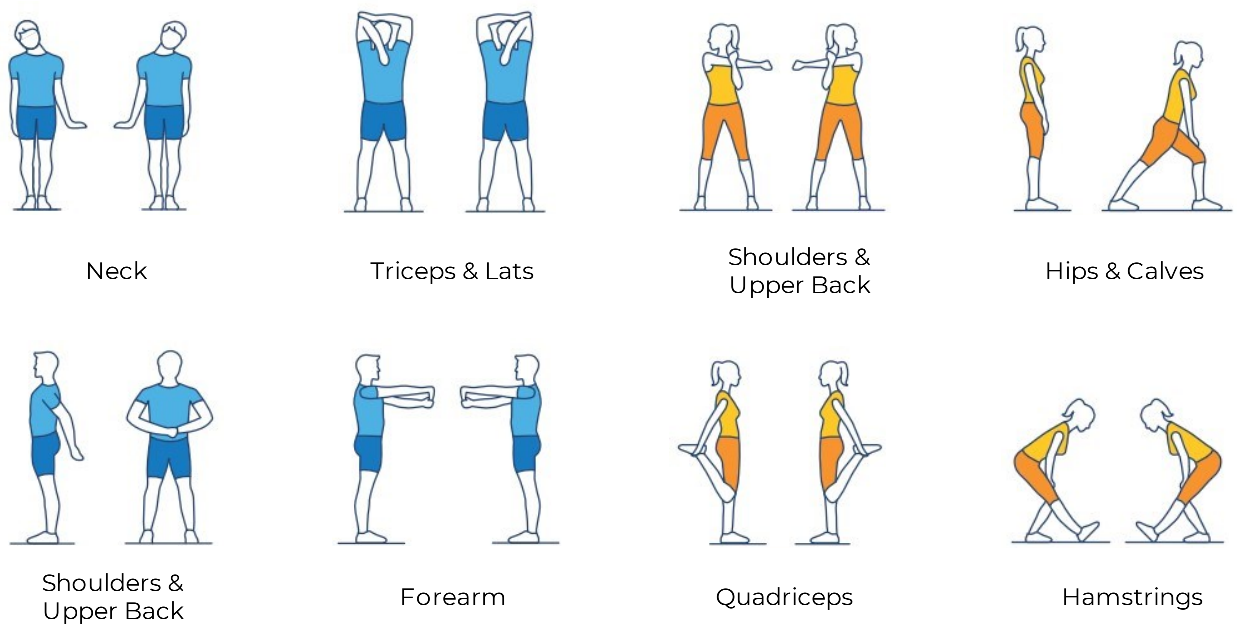
STRETCHING AFTER WORK

- Stretch when you’re warm or warm up first
- Do not stretch past the point of discomfort
- Move in and out of the stretches slowly
- Breath normally
- Don’t bounce
- Hold each stretch for 15-30s



Source: Manson Construction Co, 2014; SKANSK

EXAMPLE STRETCHES



Source: SKANSKA - Educational use only

SAFE LIFTING TECHNIQUES

How do I avoid injury?

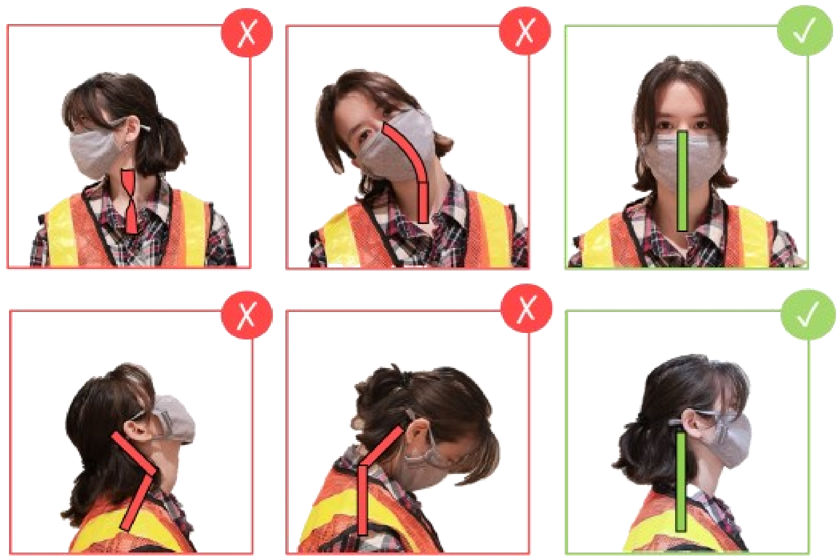
MODULE OBJECTIVES

1. Learn the main characteristics of good lifting techniques

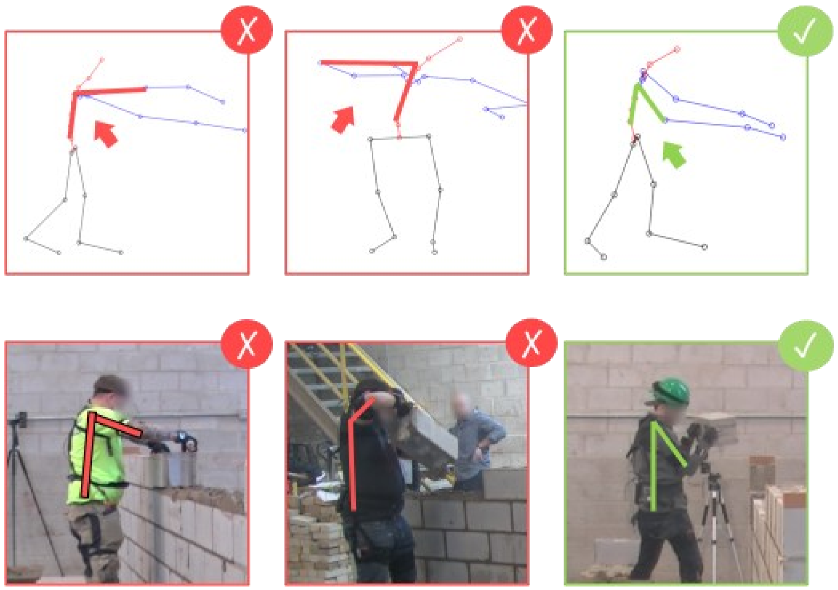
WORKING TECHNIQUES

- Doing it correctly is also doing it safely
- Demonstrations of new skills in the shop also incorporate how to do it safely

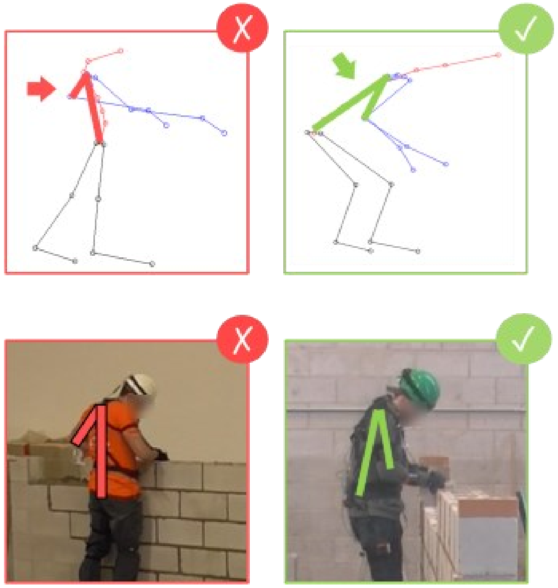
KEEP YOUR HARD HAT TOWARDS THE CEILING!



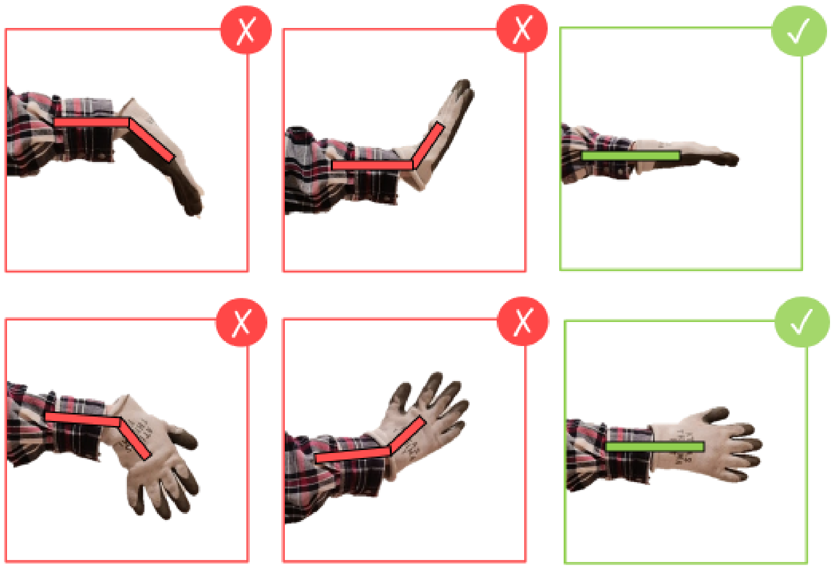
KEEP YOUR WORK BELOW YOUR CHEST!



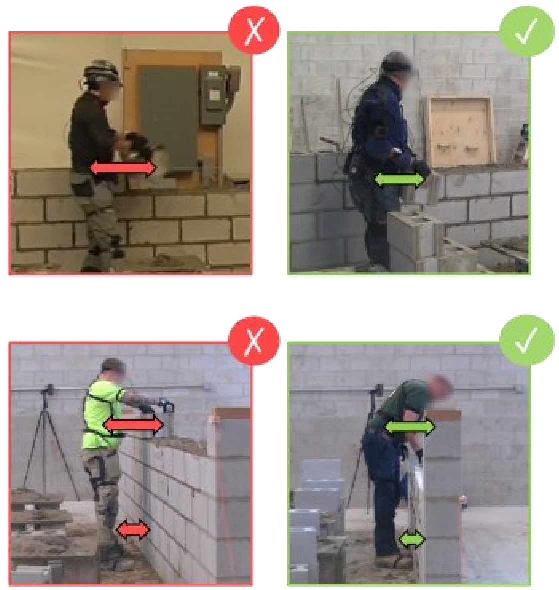
KEEP YOUR ARMS TO THE SIDE OR IN FRONT!



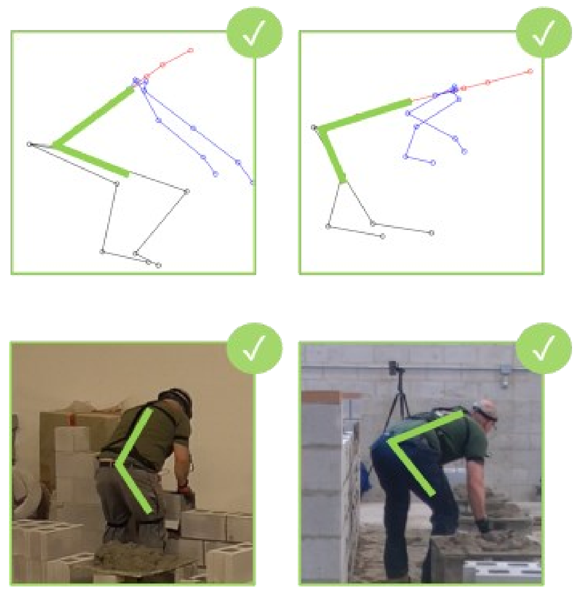
KEEP A STIFF WRIST!



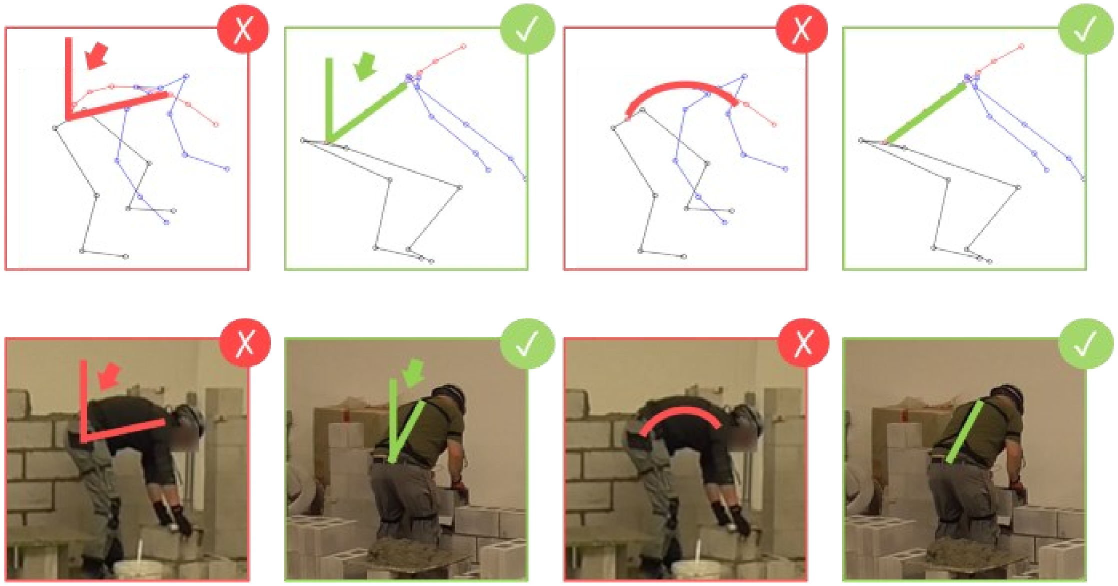
BRING THE BLOCK TOWARDS YOUR BODY



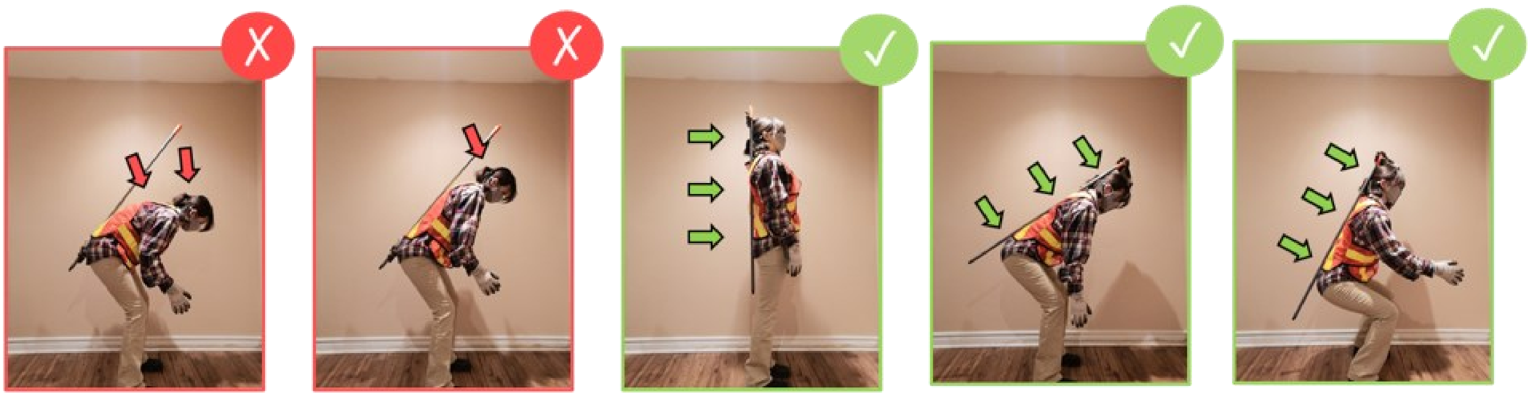
STICK YOUR BUTT OUT!
BEND AT HIPS!



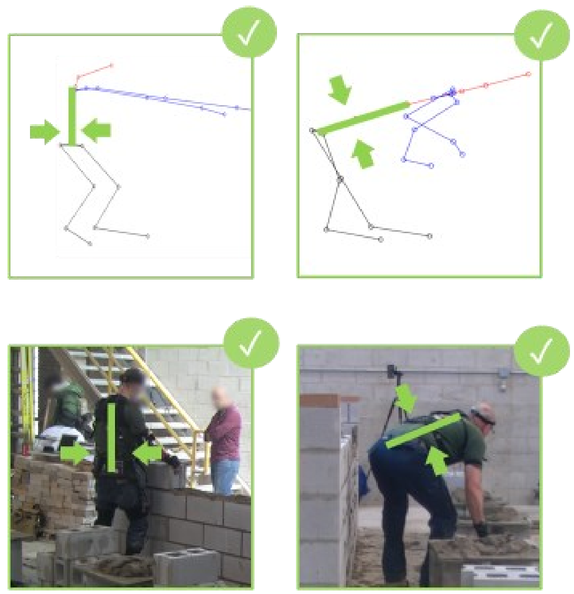
PROUD CHEST!
STICK YOUR BUTT OUT!



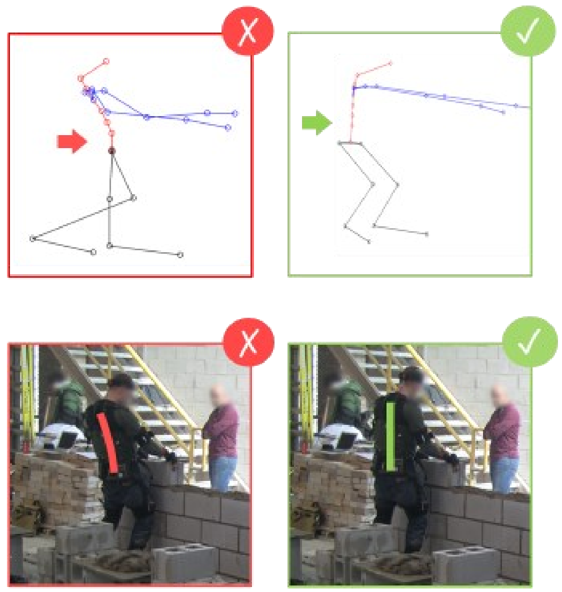
WHAT IS A NEUTRAL SPINE?



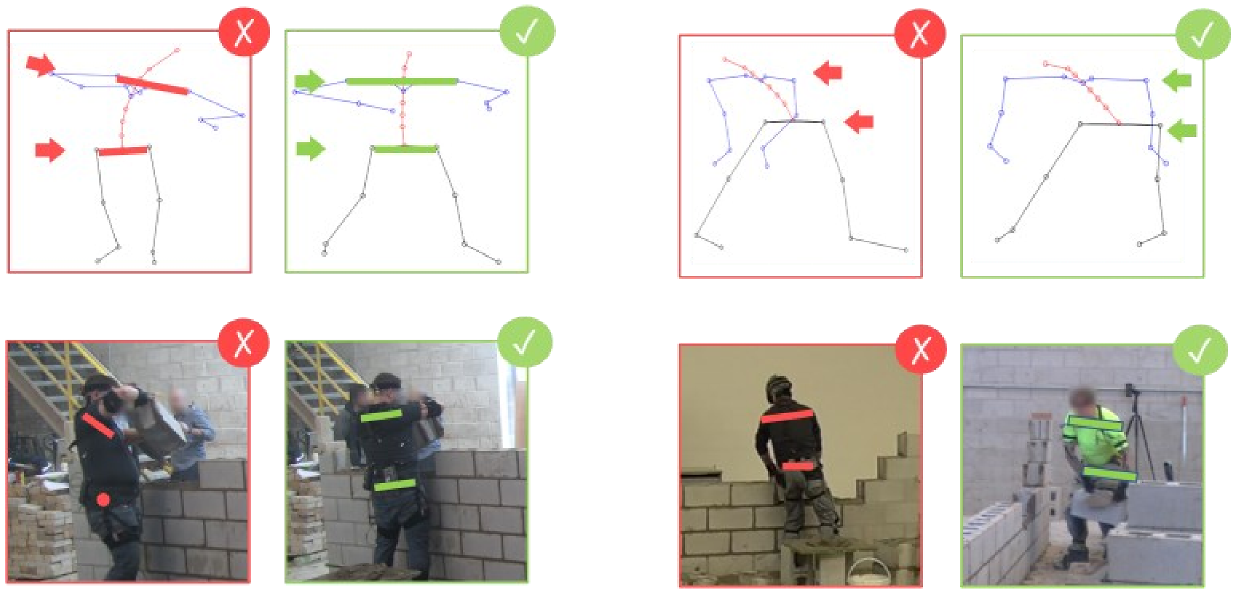
BRACE YOUR CORE



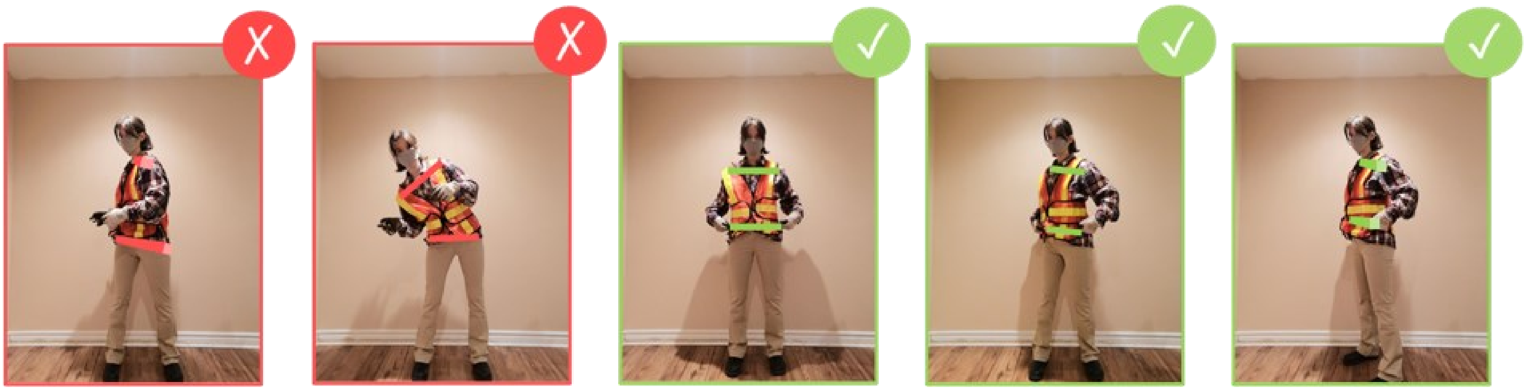
STAND TALL



SQUARE YOUR HIPS AND YOUR SHOULDERS!



SQUARING YOUR HIPS & SHOULDERS

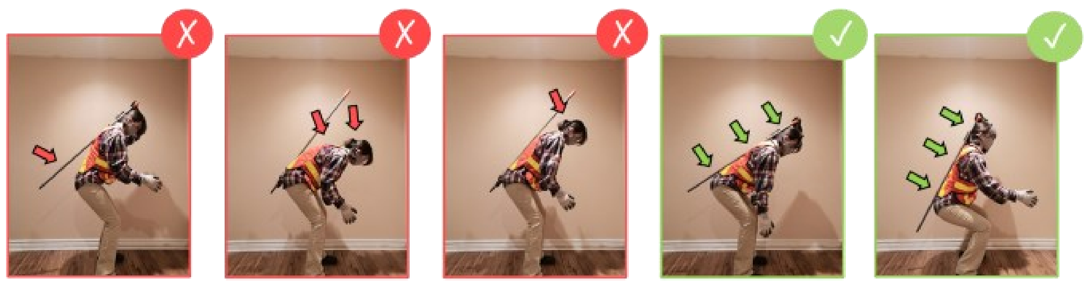


LEARNING PROPER BODY MOVEMENTS

Exercises to practice proper movement techniques

KEEPING A NEUTRAL SPINE

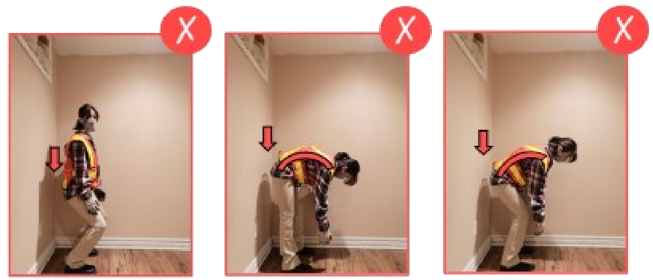
Neutral Spine: Hips and shoulders are squared. Three points of contact at the head, the upper back and the lower back are maintained throughout the movement.



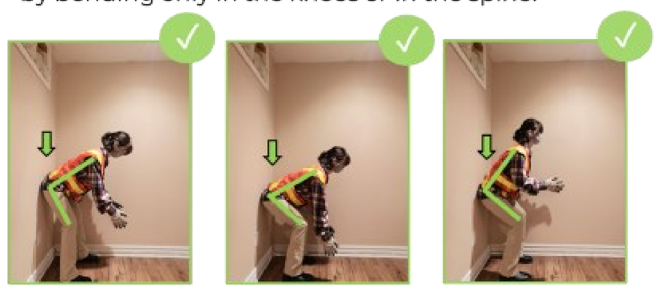
Non-Neutral Spine: All three points of contact at the head, the upper back and the lower back are **NOT** maintained throughout the movement. Think of the trunk as a single stiff unit and bend at the hips. Remember to keep the head in line as well.

BENDING AT THE HIPS

Start by standing 7-15 cm in front of a wall.



You will be unable to touch the wall with your butt by bending only in the knees or in the spine.



Touch the wall with your butt by sitting back or bending at the hips and pushing the butt out.

SQUARING YOUR HIPS & SHOULDERS

Align Hips & Shoulders: Imagine horizontal lines between your shoulders and your hips. Try to keep these lines parallel. When twisting your upper body, twist with the hips as well or move your feet to keep your shoulders and hips aligned. **Avoid** twisting your spine in a bent over position!

SQUARING YOUR HIPS & SHOULDERS

Practice: Stand with arms outstretched and both hands touching the wall at shoulder height. While keeping one hand on the wall, take your other hand and reach as far as you can across your body. Practice twisting with both your shoulder and hips at the same time.

MOTION-BASED TRAINING TOOL

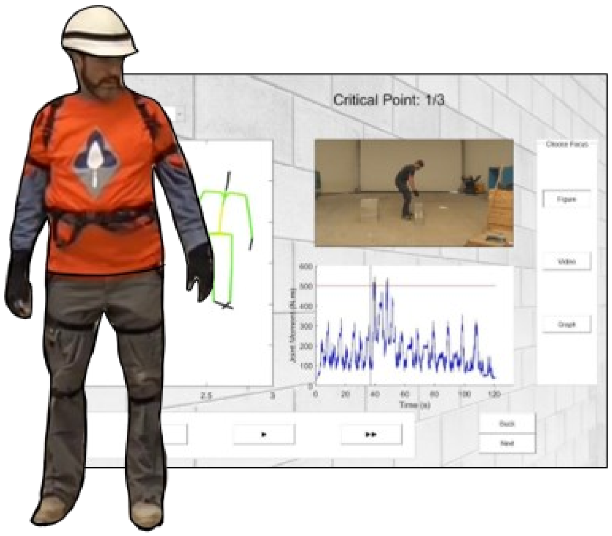
What is it & how will it help me?

MODULE OBJECTIVES

1. Understand the context of training tool and previous research findings
2. Learn what the training tool is and how it works
3. Learn how we'll be using the training tool, and its benefits

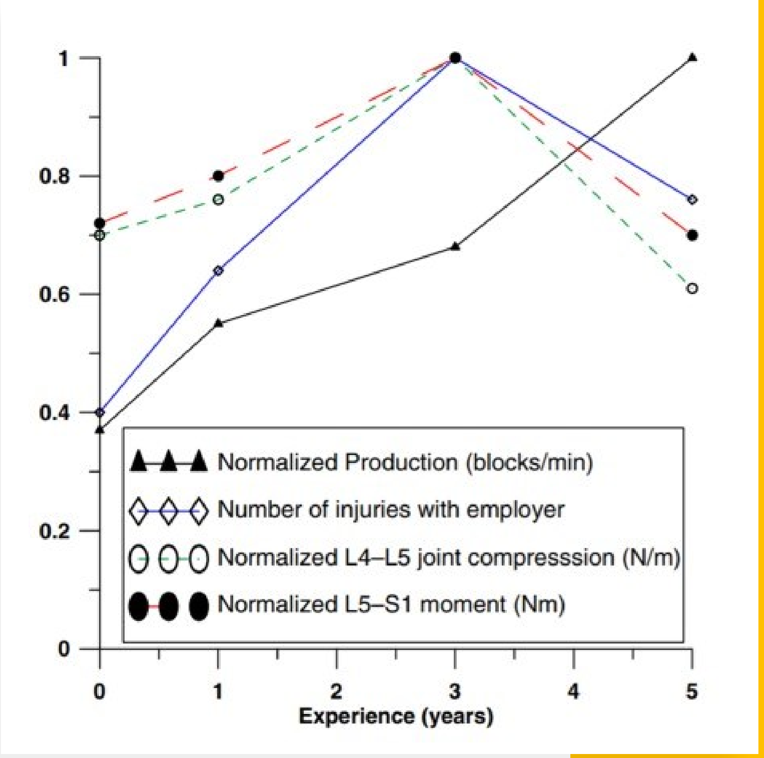
MOTION-BASED TRAINING TOOL

- Developed by the researchers at the University of Waterloo
- Based on motion studies of masons in Ontario & interviews with CMDC instructors



RESEARCH FINDINGS

- Productivity ↑ with experience
- Injury risk ↑ for 1st & 3rd year apprentices
- Injury risk ↓ for journeymen



Source: Alwasel et al., 2017

WHY ARE APPRENTICES MORE LIKELY TO GET INJURED?

- Inexperience
- Technique
- Lack of work conditioning or fitness
- Lack of training or knowledge
- Awareness and attentiveness

Based on interviews with CMDC instructors

WHY ARE APPRENTICES MORE LIKELY TO GET INJURED?

- Inexperience

Technique

- Lack of work conditioning or fitness

Lack of training or knowledge

Awareness and attentiveness

Based on interviews with CMDC instructors

COMMON ATTITUDES LEADING TO INJURY

- Lifting too much out of pride, respect or to impress
- Not getting help because it's easier or faster
- Thinking you're invincible or that it won't happen to you
- Skipping the warm-up
- Sacrificing safety for productivity

Based on interviews with CMDC instructors

SAFETY & PRODUCTIVITY

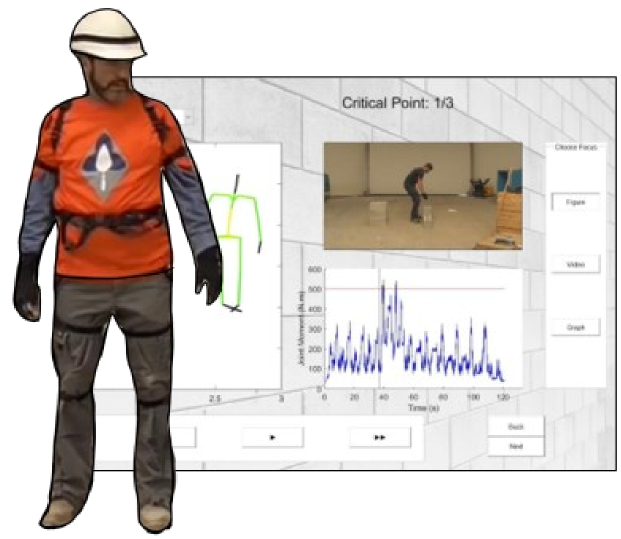
- Overworking will end up with you being sore and exhausted & can have long term impacts

- It won’t help you or your employer

- Taking care of your body is key to a long and healthy career

MOTION-BASED TRAINING TOOL

Onsite training tool designed to help apprentices learn the movement techniques of expert masons.

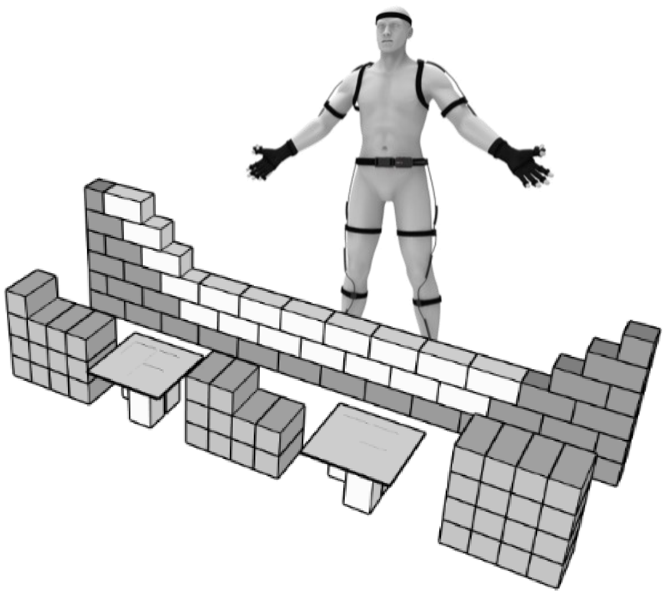


HOW IT WORKS

- Sensors collect information about your movements while building a standard wall

- Software identifies high-risk postures or joint loads

- Provides an overall score & feedback about how to improve score



HOW WE WILL BE USING IT

- Everyone will have the opportunity for assessment in the next few weeks
- Everyone will be assessed again at the end of the 8 - week course to see if you've improved
- We will continue assessments at level 2 and level 3 as a refresher

HOW IT WILL HELP YOU

- Personalized analytics and feedback
- Opportunity to identify any problem areas early on
- Can track your own progress
- Promote safe lifting techniques to reduce injury risk

Appendix H
Safe Lifting Techniques Pocket Cards and Poster

Figure 69: Safe lifting pocket cards with additional details (Large size, 7.6x12.7cm/3x5in)

Figure 70: Safe lifting pocket cards (Large size, 7.6x12.7cm/3x5in). Image true to size.

3.54

Figure 71: Safe lifting pocket cards (Small size, 5x9cm)

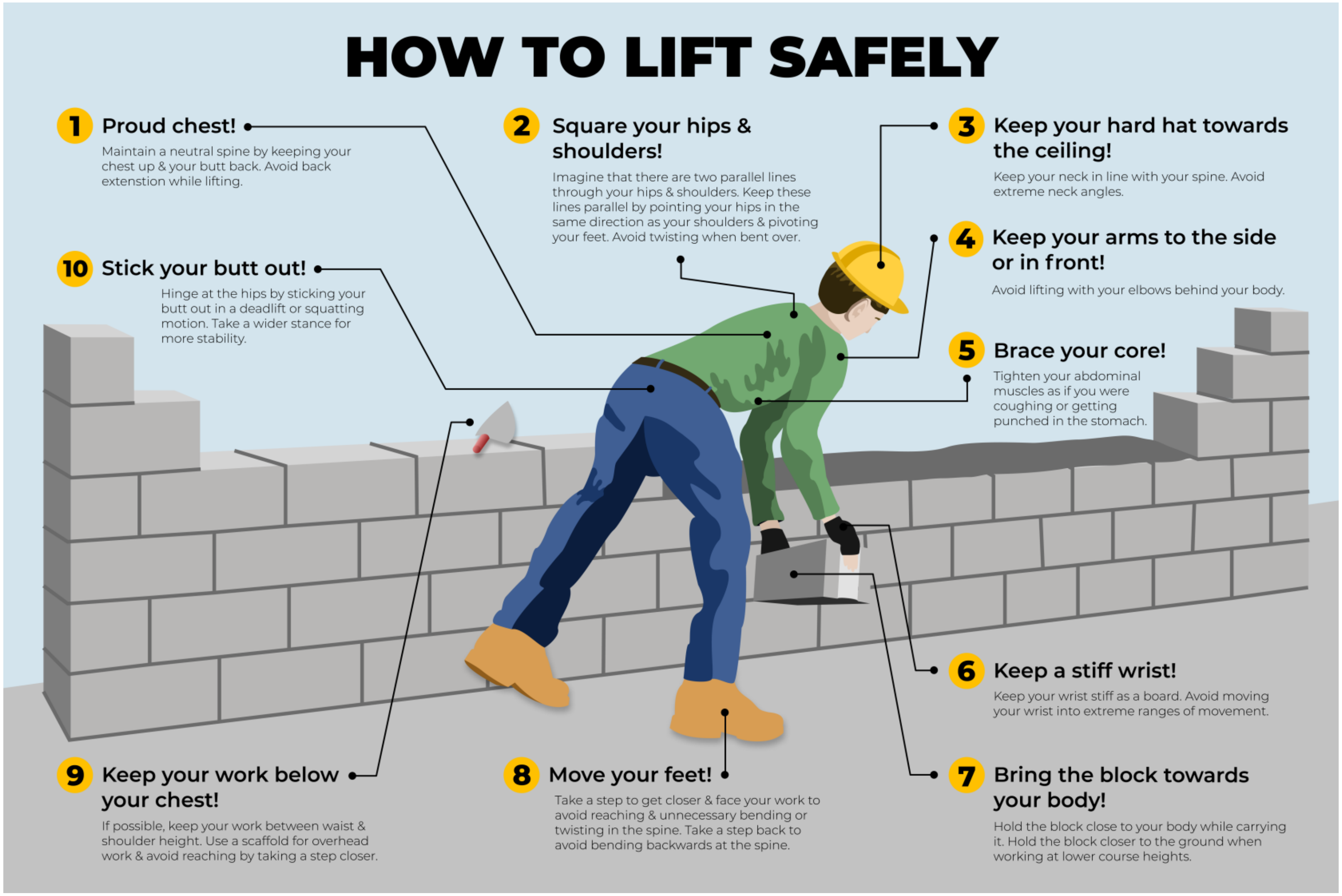
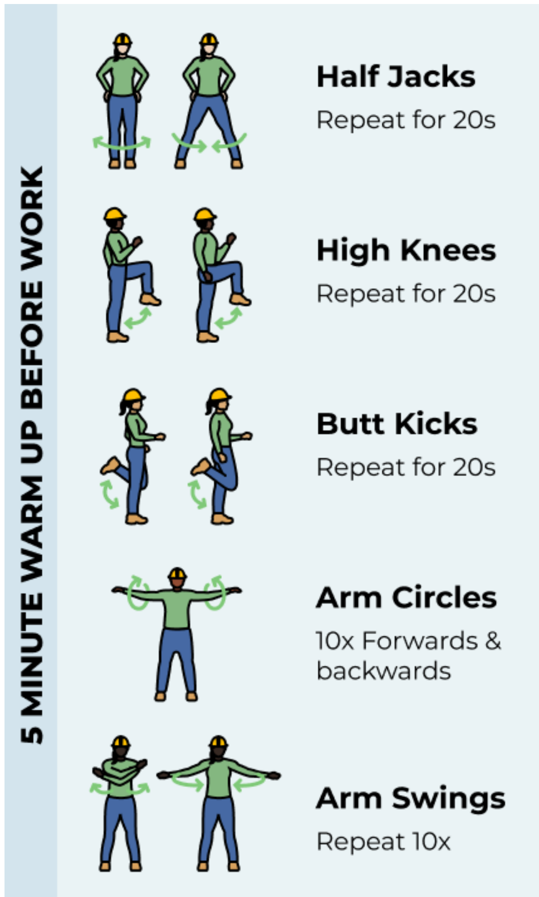


Figure 72: Safe lifting poster (91.4x61cm/36x24in)

Appendix I
Warm Up Routine Pocket Cards and Poster



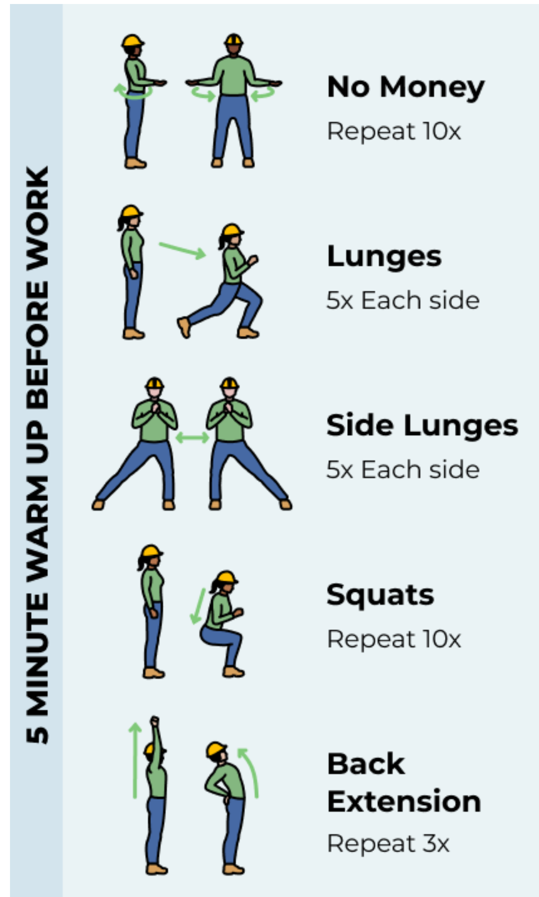


Figure 73: Warm up pocket cards (Large size, 7.6x12.7cm/3x5in)

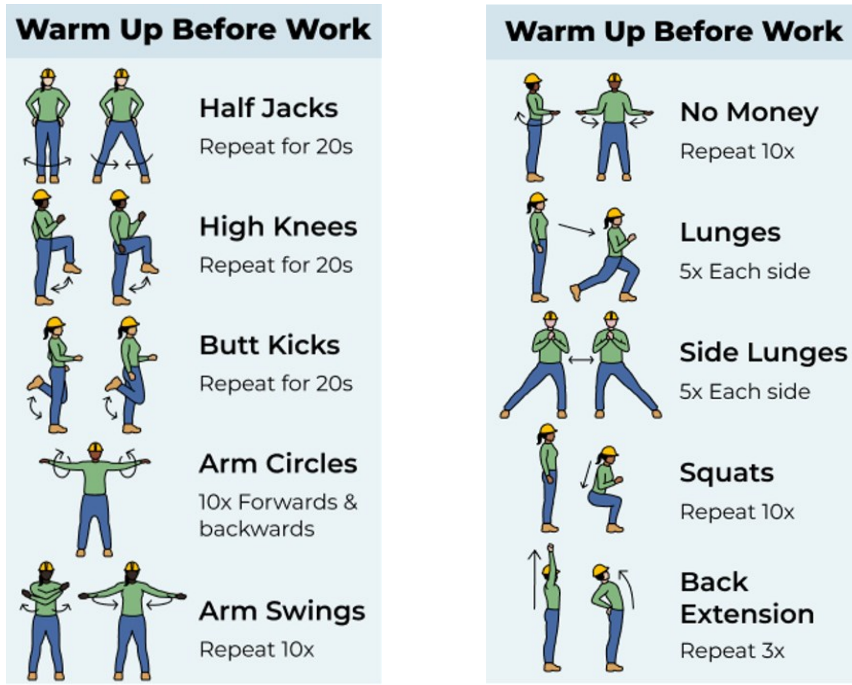


Figure 74: Warm up pocket cards (Small size, 5x9cm)

Figure 75: Warm up routine poster (91.4x61cm/36x24in)