VIRTUAL ERGONOMICS AND GAMING TECHNOLOGY

VIRTUAL ERGONOMICS AND GAMING TECHNOLOGY FOR POSTURE ASSESSMENT: FROM AUTOMOTIVE MANUFACTURING TO FIREFIGHTING

By

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LAY ABSTRACT

Virtual ergonomics (VE), which uses digital human models in virtual workstations, allows for efficient and detailed ergonomic assessments of tasks that are otherwise difficult or impossible to perform. However, more research is needed to identify tool improvements for both traditional and new applications. This work proposes, evaluates, and ultimately recommends a set of postural guidelines for the posturing of digital human models to ensure accurate simulation and subsequent assessment of real assembly-line worker movement patterns. Next, firefighter ergonomics, a relatively new application for VE tools, is introduced by first describing the injury risks associated with common fire suppression tasks. The strengths, limitations, and potential of applying VE tools to firefighting ergonomics are then highlighted through an example of simulating the high-rise pack lift task using two VE tools. Overall, the results contribute to the evolving field of VE by challenging current methodologies and highlighting new opportunities for VE tools.

ABSTRACT

Virtual ergonomics (VE) tools have had an impressive impact on the automotive, aviation, and defence industries. Despite the progress made in the last four decades, the tool complexity and application potential in other industries continues to invite improvement opportunities. Firefighting is an occupation with a high musculoskeletal injury burden that can benefit from innovative VE tools. This dissertation aims to: 1) improve VE tools for traditional and novel applications, and 2) identify injury risk to firefighters during fire suppression tasks.

This dissertation begins by proposing a set of joint-specific and whole-body posturing guidelines for the manual manipulation of digital human models (DHMs) in the context of automotive manufacturing. Simulation accuracy improved with the implementation of posturing guidelines. These findings are useful instructions for virtual simulation ergonomists, software developers of posture prediction algorithms, and those charged with determining manufacturing ergonomics protocols.

Descriptive ergonomic analyses of 48 firefighters in full bunker gear performing three common fire suppression tasks were then performed to identify the required ergonomic action needed for these tasks. Next, two VE tools (Jack and 3DSSPP) and Microsoft Kinect® 3D motion capture data were used to conduct an in-depth analysis of the most difficult task, the high-rise pack lift. The analysis included developing a methodology for modeling the external loads due to personal protective equipment. In addition to describing the firefighter injury risk exposure during common fire suppression tasks, the results highlight the strengths, limitations, and areas for further improvement of VE technology.

Overall, VE tool improvements include suggesting guidelines for manual DHM posturing, understanding the strengths and limitations of using 3D motion capture gaming technology for posturing DHMs, and developing strategies to account for external loads due to personal protective equipment. Following these improvements, VE technology shows promise as an ergonomic assessment tool for firefighters.

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reaction forces are relative to the coordinate system defined by the horizontal and vertical components of the SCBA, as shown in Figure 1.

LIST OF ABBREVIATIONS

AC	Action classification
AL	Action limit
BMI	Body mass index
CAD	Computer-aided design
DHM	Digital human model
MMH	Manual materials handling
MMJM	Manual manikin joint manipulation
MSDs	Musculoskeletal disorders
NIOSH	National Institute for Occupational Safety and Health
OWAS	Ovako Working Posture Analyzing System
PPE	Personal protective equipment
REBA	Rapid Entire Body Assessment
RH	Real height
RMSE	Root mean squared error
RULA	Rapid Upper Body Assessment
SCBA	Self contained breathing apparatus
S1	Study 1
S2	Study 2
SSP	Static strength prediction
TSF	Total solved force
T%C	Total percent capable
VE	Virtual ergonomics

DECLARATION OF ACADEMIC ACHIEVEMENT

This this contains the doctoral research of Tara Kajaks and has been prepared in a "sandwich" format as outlined in the McMaster University School of Graduate Studies' Guide for the Preparation of Theses. The thesis begins with a general introductory chapter (Chapter 1), followed by three studies that have been prepared as individual manuscripts (Chapters 2-4). The final chapter is a general discussion (Chapter 5), that summarises the research findings and provides insight into future directions for this research.

Chapter 2 – Published in the "International Journal of Human Factors Modelling and Simulation"

Kajaks, T., Stephens, A., & Potvin, J. R. (2011). The effect of manikin anthropometrics and posturing guidelines on proactive ergonomic assessments using digital human models. *International Journal of Human Factors Modelling and Simulation*, *2*(3), 236–253. https://doi.org/10.1504/IJHFMS.2011.044512

Contributions

Chapter 2 was published in the International Journal of Human Factors Modelling and Simulation in 2011. This study was designed by Tara Kajaks and Dr. Jim Potvin. Data collection was carried-out under the leadership of Tara Kajaks, with the support of Dr. Jim Potvin and Allison Stephens to recruit experienced virtual ergonomists. Tara Kajaks lead the data analysis and interpretation, as well as the preparation of the manuscript. Dr. Potvin and Allison Stephens provided input into the data analysis and reviewed the drafts of the prepared manuscript.

Chapter 3 – Prepared for submission to "Applied Ergonomics"

Kajaks, T., Galea, V., Vrkljan, B., MacDermid, J. Posture evaluation of firefighters during simulated fire suppression tasks. Prepared for submission to the "Applied Ergonomics"

Contributions

Chapter 3 has been prepared for submission to “Applied Ergonomics”. This study was designed by Tara Kajaks and Drs. Joy MacDermid and Kathryn Sinden. The Hamilton Firefighter’s Association also contirbuted to the study design by identifying challenging fire suppression tasks to evaluate and assisting with firefighter recruitment. Tara Kajaks and Dr. Sinden collected the data simultaneously, with each researcher responsible for independent outcome measures for different study purposes. With consultation from Drs. Joy MacDermid, Vickie Galea, and Brenda Vrkljan, Tara Kajaks lead the data analysis and interpretation. The original draft of the manuscript was prepared by Tara Kajaks and was critically reviewed by the co-authors.

Chapter 4 – Prepared for submission to the “International Journal of Human Factors Modelling and Simulation”

Kajaks, T., Vrkljan, B., Galea, V., MacDermid, J. Ergonomic assessments of firefighters in full bunker gear using digital human modeling software. Prepared for submission to the “International Journal of Human Factors Modelling and Simulation”

Contributions

Chapter 4 has been prepared for submission to the “International Journal of Human Factors Modelling and Simulation”. This study used data collected by Tara Kajaks, as described in Chapter 3, for the purpose of doing biomechanical modeling and digital human simulations for ergonomic assessments. Tara Kajaks lead the development of the methodology, and carried-out the data analysis and interpretation with consultation from Drs. Joy MacDermid, Vickie Galea, and Brenda Vrkljan. The original draft of the manuscript was prepared by Tara Kajaks and was critically reviewed by the co-authors.

CHAPTER 1: GENERAL INTRODUCTION

1. Virtual Ergonomics

1.1 Background

The use of digital human models (DHM), or avatars, for virtual ergonomics (VE) application is becoming one of the most powerful methods for fast, comprehensive, and cost-effective ergonomic analyses. VE allows for computer aided design (CAD) drawings to be merged with a DHM within a specialized software program with embedded ergonomic analysis modules and, therefore, has the benefit of assessing injury risks in either the early product development stages or in workplace task analysis. Indeed, for many of the VE tools, the realistic digital human and environmental 3D renderings produced for the ergonomic analyses have played a large role in convincing decision makers of the need for change (Perez & Neumann, 2015) and, consequently, in the ability of the tools to have such a positive impact on the field of ergonomics.

VE technology has been in use for over four decades primarily in the automotive, aerospace, and defense industries for assessing human fit, reach, and strength capabilities for designing spaces and tasks as well as workplace musculoskeletal injury risk assessment (Chaffin, 2008; Sanjog et al., 2015). The largest gains from the use of this technology have arguably been reported by the automotive manufacturing sector (Brazier et al., 2003; Malone & Porto, 2016), which has seen injury rates fall from 10.2% in 2003 to 5.6% in 2010 (BLS, 2011). Although it is difficult to determine exactly how much of this injury rate reduction is directly associated with the adoption of VE practices, Malone et al. (2016) recently reported an ergonomic issue reduction of between 66% to 75% at the onset of vehicle production resulting from the early identification of issues using VE tools. Similarly, Falck and Rosenqvist (2014) developed a model for calculating the costs associated with poor assembly ergonomics and found that high injury risk ergonomic issues had the potential to yield five to eight times as many quality issues as low-risk issues. The cost of addressing these quality issues early in the manufacturing process decreased considerably compared with detection at later stages of the manufacturing process (9.2 times greater than early issue detection) and post-build stages (12.2 times greater than early issue detection).

Significant benefits exist to using VE tools including reducing worker injuries, improving production quality, and, ultimately, cost savings to companies. Nonetheless, there is still considerable potential for continued development of these tools (Chaffin, 2005; Feyen, 2007; Perez & Neumann, 2015). Barriers to more mainstream use of VE tools include the expertise required to use VE tools, the software purchase costs, particularly for small and medium businesses, and the limited ability of these tools to account for human variability (Perez and Neumann, 2015). Feyen (2007) further suggest that VE tools should better consider the synergy between cognitive and physical performance to produce the observed behaviours of workers. This consideration should include the impact of external influences including human activities, equipment, and environmental factors, as well as physiological and emotional interactions. “Ultimately”, says Feyen (2007), “we are looking for human models that, among other things, can adapt to the environment, get tired, make mistakes and become frustrated or angry – just like we do”. Similarly, Chaffin (2008) contends that the merging of cognitive and physical human models is a necessary advancement in human performance modeling. As described below, these human modeling advances are mostly specific to the DHM posture prediction method embedded within several VE software packages called posture prediction. However, VE improvements are still required at more basic levels. Two decades following the 1996 SAE survey of 250 designers regarding recommendations for the improvement of VE, many of the available tools are still limited in their ability to account for clothing restrictions and external forces caused by personal protective equipment (PPE), assess dynamic movements over a period of time, and simulate realistic postures in different constrained and unconstrained environments with minimal task inputs (Chaffin, 2008).

This introductory chapter begins by providing a broad overview of VE uses, including reactive and proactive ergonomics, with an emphasis on VE use in the automotive sector as the most common application of VE tools. The methodologies employed to complete VE assessments are then introduced, followed by a discussion of new observational methods for use with VE tools. Finally, the issue of firefighter injury prevention is presented along with proposed solutions as they relate to the application of VE tools to this workforce.

1.2 Reactive and Proactive Virtual Ergonomics

A benefit to VE tools over traditional ergonomic tools is that they can be used for both reactive or proactive ergonomics (Chaffin, 2005). Traditional ergonomic tools are typically reactive, and are used to assess the injury risks associated with a real worker within his or her workstation. These assessments often occur as a response to a request from the worker or supervisor due to pain or discomfort reports, an identified injury, or a suspected injury risk. The costs associated with this approach can be great, particularly if funds have already been dispensed to cover direct and in-direct injury costs, or if substantial changes are required to the workstation or work protocol, particularly if these changes: 1) impact the broader work environment including shutting down an assembly line, or 2) require the procurement of new tools or materials. Additional in-direct costs due to the requirement for reactive ergonomics include production issues such as reduced productivity quality control and recall costs (Falck et al., 2010).

Proactive assessments, which occur well before actual or perceived exposure to injury risks occur, can lead to substantial costs savings (Chaffin, 2005; Falck & Rosenqvist, 2014). In the case of the automotive manufacturing industry, proactive ergonomics is often tied with product development whereby manufacturing processes are modelled in a virtual environment and digital humans are manipulated within the environment such that they build a virtual vehicle (Brazier et al., 2003; Stephens & Godin, 2006). Given that at this stage of the design and manufacturing process no actual prototypes are used, the assembly line has yet to be built, vehicle components have yet to be purchased, and a worker has yet to be assigned to the workstation, the financial costs of identifying a potential future injury risk are relatively minimal (Chaffin, 2005; Falck et al., 2010). If an ergonomic issue is identified, the design or manufacturing engineering team can often easily modify the workstation task. However, challenges to the ergonomists conducting the VE analysis include: 1) estimating the DHM postures without the benefit of knowing how a real worker might actually perform the task, and 2) unknown anthropometrics of the actual worker. Depending on the VE software being used, possible resources available to the ergonomists to assist with the first challenge include posture prediction algorithms, experiential knowledge if using DHM manual manipulation, and motion capture data from simulated mock-ups of the virtual prototype (see section 1.3 for a description of these methods). Addressing the second challenge is often performed by using either a standardized DHM, for example using a 50th percentile female as a surrogate for the worker who may be considered to be at an elevated risk of musculoskeletal injury due to their relatively small stature and decreased strength compared to the rest of the workforce, or selecting several DHMs with anthropometrics that are more representative of the breadth of the workforce including small, average, and larger workers.

Although VE tools are typically used reactively and proactively in design and manufacturing applications, they can also be helpful to understand the injury risk factors for most manual materials handling tasks during fireground operations, which are typically fire suppression tasks performed at active fires. For instance, reactive ergonomics may be required as a result of a reported or suspected injury during a hose manipulation or tool operation task. VE tools may also be used reactively or proactively to assess the risks of firefighters working with compensatory movement strategies due to sub-optimal health and fitness statuses as they relate to the safety for the firefighter and his or her co-workers, as well as the civilians they are trying to help. Additionally, proactive ergonomics may be used to assess the ergonomic impact of potential equipment or protocol modifications. Ergonomists wishing to use VE tools for the assessment of firefighter tasks not only have the challenges described above with respect to reactive and proactive ergonomics, but they must also consider the impact of the external loads caused by the PPE as well as any environmental factors such as surroundings and climate. With the steady evolution of VE tools, it is expected that the firefighting occupation will soon be able to benefit from the use of VE tools for understanding and modifying musculoskeletal injury risks.

1.3 Virtual ergonomics methods

An important aspect of VE is accurately posturing the DHM such that it is representative of human movement given any relevant task constraints for the scenario under investigation in order to determine the associated injury risk. Although posture, combined with other workload exposure factors (e.g. force, repetition, and duration), is often used as a measure to assess musculoskeletal injury risk, it is important to note that unfavorable postures, as determined by the respective ergonomic tool, do not necessarily imply the presence or imminent development of an injury. Indeed, mechanisms of injury are often much more complex than a simple assessment of posture and workload exposure. For instance, while there is epidemiological evidence demonstrating an increased risk of knee osteoarthritis in adults who perform frequent occupational activities such as squatting (Mcwilliams et al., 2011), observational ergonomic tools do not directly measure the internal structures of the body, for instance the knee cartilage thickness as a measure of the presence and progression of knee osteoarthritis, in order to definitively diagnose the presence of a current or impending injury. However, the posture assessment tools embedded in the leading VE tools are reliably used within the ergonomics community and have often been validated for the purpose of determining levels of musculoskeletal injury risk (Li & Buckle, 1999).

DHM software packages have different posturing strengths and capabilities; however, three general methods are commonly used to posture the DHM in the virtual environment for subsequent ergonomic assessment. These methods include: 1) use of posture prediction algorithms to drive the movements of the DHM based on a set of task constraints, 2) manual manipulation of each joint on the DHM by an ergonomist until the desired posture is achieved, and 3) use of motion capture technology to track the movements of a real human, which are then streamed into the VE software and used to drive the DHM.

The posture prediction method is the newest strategy in VE technology, and, depending on the model, is often based on principles of biomechanics, physiology, motor behaviour, and/or motor control (e.g. Abdel-malek et al., 2006; Chaffin, 2005; Reed et al., 2006). Posture prediction methods are currently in practice in several DHM software (e.g. Jack, Siemens PLM Solutions, TX, USA and Santos, SantosHuman Inc., Coralville, IA, USA). They are also considered to be the ideal method by some industries (e.g. Stephens and Godin, 2006) due to their implementation efficiency. However, before more mainstream use is readily adopted, more work is needed to ensure that the fidelity of the predictive algorithms is sufficient to understand not just how a breadth of humans ought to move from a biomechanical perspective, but also how they choose to move by considering human motor behaviour and control strategies (Dukic et al., 2007; Kajaks & Lyons, 2012). Thus, today, most virtual ergonomic efforts currently rely on either the manual manipulation method, the motion capture method, or a combination of the two.

Manual manipulation was the first method available to those using DHM technology, and is still widely used due to its need for minimal resources (i.e. a computer, the DHM software, a VE expert, task instructions, and, where appropriate, a CAD environment). However, depending on the complexity of the task, posture and virtual environment, manually manipulating a DHM to achieve a specific posture can be very time-consuming (Lämkull et al., 2006). Furthermore, with the manual manipulation method, the DHM user must rely on their own understanding of human movement to estimate a feasible DHM posture thereby introducing both subjectivity and the potential for incorrect assumptions about human movement. However, studies investigating the accuracy of the manual manipulation method have shown that experienced ergonomists can predict postures with good accuracy (McInnes et al., 2009; Potvin et al., 2008)), particularly if they use a set of posturing guidelines (Kajaks et al., 2011).

Where possible, some ergonomists and researchers prefer to use the motion capture method (Stephens and Godin, 2006), which involves driving DHMs with real human movement data to ensure the most accurate postures possible. The traditional motion capture method can be costly as it often requires the purchase of expensive motion capture equipment, a motion capture laboratory space with the tools needed to build a simulated environment (e.g. a mock vehicle for automotive manufacturing ergonomics testing), participant recruitment, and a motion capture expert to collect the data. More recently, however, VE software developers have introduced modules that allow for data from low-cost and easy-to-use motion capture equipment, such as the Microsoft Kinect® system, to drive the DHMs within the software. Not only does the introduction of the Kinect system make using the motion capture method much more accessible to a larger user group, but the fact that it is both compact and uses markerless technology to predict joint centres enables motion data collection to move away from controlled laboratory environments and into the field (Colombo et al., 2013; Diego-mas & Alcaide-Marzal, 2014). Although the pairing of the Kinect and DHM software, such as Jack, has the potential to offer great value to a breadth of ergonomic applications, there are strengths and limitations that any potential user must understand before deciding to collect field data using the Kinect in combination with DHM software.

1.4 Microsoft Kinect® and virtual ergonomics tools

The Microsoft Kinect® system was released in 2010 as a component of the Microsoft Xbox 360 gaming console. Shortly after it's release, Microsoft made the software development kit available to the computing community. Armed with the software development kit, researchers have since been developing new and innovative ways of using the Microsoft Kinect® system. The Microsoft Kinect® system contains two data sensors: 1) an RGB (red green blue) sensor for collecting 2D color data and 2) an infra-red light sensor for collecting 3D depth data. When these data sources are combined, 3D mapping of images within the field-of-view can achieved. An algorithm embedded in the software development kit can then use this information to virtually assign a 21-joint full-body skeleton to the image of a human within the field-of-view. The accuracy of the assigned skeleton has been reported as sufficient for ergonomic and clinical application in optimal conditions (Clark et al., 2012; Diego-mas & Alcaide-Marzal, 2014; Schmitz et al., 2014), such as when the human within the field-of-view is minimally clothed and standing with their frontal plane directly facing the camera at a distance of between 1 m and 3 m, the quality of the data decreases when a body segment is partially or fully occluded, is not fully within the field-of-view, or increases the level of sophistication of their activities beyond slow basic movements (Obdrzalek et al., 2012; Patrizi, Pennestrì, & Valentini, 2016; Xu & Mcgorry, 2015). Nonetheless, the benefits of using this tool are great, and include: its low cost compared to most other optical motion capture tools, its ease-of-use including marker-less data collection protocol, its portability between laboratory and field-friendly environments, and access to the software development kit for the creation of customized software and applications. These benefits have allowed the Microsoft Kinect® to be used beyond the world of gaming, including physical rehabilitation (e.g. Bonnechere et al., 2014; Chang et al., 2011; Clark et al., 2013;

Fernandez-Baena et al., 2012) and workplace ergonomics (e.g. Colombo et al., 2013; Diego-mas & Alcaide-Marzal, 2014; Haggag et al., 2013; Patrizi et al., 2016; Plantard et al., 2015; Ray & Teizer, 2012).

Two common approaches exist for using the Microsoft Kinect® for ergonomic assessments. First, researchers and practitioners can develop their own customized ergonomic programs that are based off existing tools including the Occupational Safety and Health Association's (OSHA) recommended weight limit (RWL) for lifting, the Ovako Working Posture Analysis System (OWAS) (Diego-Mas and Alcaide-Marzal, 2014), the Rapid Upper Limb Assessment (RULA) Tool (e.g. Haggag et al., 2013; Plantard et al., 2015), or a customized ergonomic assessment method based on posture classification using the Kinect skeleton data (Ray and Teizer, 2012). Alternatively, the Microsoft Kinect system can be used with existing DHM software, such as Jack, to both anthropometrically scale the DHMs (Puthenveetil et al., 2015) and to drive the DHM to simulate the movements of the actual participant in the field-of-view of the Microsoft Kinect® system (Colombo et al., 2013).

In both approaches, the Microsoft Kinect® can be used as a real-time motion capture system to yield instantaneous ergonomic feedback to the participants performing the movements. As such, and combined with its portability to many workplaces, the Microsoft Kinect® system shows potential as an important component of both ergonomic assessment tools and ergonomic training tools (Martin et al., 2012). However, the current limitations of the Microsoft Kinect® must also be recognized. These limitations include:

1) collecting data from a single point of view, 2) occlusion of one or more body segments due to participant orientation, environmental factors, or posture, 3) limited sampling rate for faster movements, 4) accuracy of the skeletal mapping, joint centre estimations, and body segment lengths, and 5) compatibility of the Microsoft Kinect skeleton to map onto the skeleton of the DHM (Colombo et al., 2013; Diego-Mas et al., 2014; Haggag et al.,2013; Xu and McGorry, 2015; Patrizi et al., 2015). Although not discussed in the literature, an additional limitation of using the Microsoft Kinect® system as a motion capture tool for VE practices may be the accuracy of skeletal estimations when field-relevant occupational clothing is worn, such as firefighter PPE. Despite these current limitations, the technology and software solutions available to use innovative tools such as the Microsoft Kinect® system with VE practices are constantly evolving given the motivation of the research community to see the successful "marriage" of these tools. Thus, currently, the Microsoft Kinect® may serve as a better support tool for ergonomic assessment rather than a replacement tool for human assessment (Diego-Mas et al., 2014).

2. Firefighters

2.1 Firefighter Injury Rates

Firefighting is a dangerous occupation that presents many types of health-related risks to its workers. The physically demanding nature of the work leaves firefighters susceptible to both acute injuries and chronic diseases and disorders affecting their musculoskeletal

(Poplin et al., 2012) and cardiovascular systems (Smith, 2011; von Heimburg et al., 2006). The National Fire Protection Association (NFPA) estimates that of the 68,085 injuries reported in the US, 55.7 % of the reported injuries were musculoskeletal strains, sprains, or pain (Haynes & Molis, 2016). Most of these injuries (42.8% of total injuries) occurred during fireground operations, although there is emerging evidence showing that many firefighter injuries also occur during training activities (Frost et al., 2015, Frost et al., 2016). 52.7% of fireground injuries were strains and sprains, and were equally caused by both overexertion and strain (27.2%), and falls, jumps, and slips (27.2%). The results of this report are representative of average fire departments across the U.S.. However, it is important to note that the firefighter task responsible for the injury can be quite variable across fire departments both within the U.S. and internationally (Burgess et al., 2014; Frost et al., 2016; Poplin et al., 2012). While these deviations may be a function of injury reporting biases, they may also be related to risk management approaches (Burgess et al., 2014) or the use of firefighter wellness programs, which, by 2005, only 20% of U.S. fire departments had adopted (TriData Corporation, 2005). However, overall, fireground operations are most commonly reported as the leading duty for firefighter injuries, with the handling of uncharged and charged hoses responsible for most of these injuries (Burgess et al., 2014).

Firefighter injuries most commonly affect the lower extremities, torso, and upper extremities, although the statistics and joint specificity vary by research project (Frost et al., 2016; Kajaks & MacDermid, 2015; Poplin et al., 2012; WSIB, 2016). Burgess et al.

(2014) investigated 15 different fire departments world-wide (4 from Commonwealth countries, 5 from Japan, and 6 from the USA) and found that the cumulative results across all fire departments showed that most injuries occurred in the torso (40.2%), followed by the lower extremity (30.4%), and upper extremity (13.2%). However, at the level of the individual fire departments, the most commonly injured region was the lower extremity (14 fire departments), followed by the torso (5 fire departments) and the upper extremity (1 fire department). Data from the Tuscan Fire Department in Arizona, USA (Poplin et al., 2012) and the joint firefighter and police injury data from the Workplace Safety and Insurance Board (WSIB) in Ontario, Canada (WSIB, 2016) show that the most commonly injured body regions are: 1) the lower extremity (44.6 % and 27.19%, respectively), 2) the Back (32.2 % and 19.5%, respectively), and 3) the upper extremity (17.6% and 16.0%, respectively). Frost et al. (2016) studied the costs of sustaining sprain and strain injuries to common body regions by firefighters from the Calgary Fire Department in Alberta, Canada and found that the greatest costs are due to injuries sustained at the knee (28.3% of total injury costs), followed by the back (18.1 %), and shoulders (13.8 %). These injury statistics demonstrate a need to better understand the loads experienced in each of these common injury locations, and offer an indication of the body regions on which to prioritize injury prevention efforts.

In Ontario, firefighter injury data is available through the provincial worker's compensation board called the Workplace Safety and Insurance Board (WSIB). In the WSIB database, firefighter and police injury data are grouped, which makes precise estimates of injury burden difficult. Nonetheless, the data show that firefighters and police officers are two of the leading occupations for injuries in Ontario, with 1362 total injuries reported in 2015, or 2.6% of all province-wide WSIB work-related injury claims. Of WSIB Schedule 2 occupations, firefighters and police officers are second only to primary and secondary school educators in the number of reported injuries. An important aspect of the WSIB Schedule 2 system is that the employers do not pay an annual premium for insurance coverage, but rather they are individually liable to cover all costs resulting from a work-related injury or illness. In this type of system, the employers have incentive to implement health and safety training to help reduce the risk of, and the subsequent costs associated with, work-related injury or illness. Several fire departments across Ontario are actively engaged in developing health and wellness programs to help keep their firefighters safe and healthy. Examples include the Firefighter Illness Remediation Enterprise-Work-Accommodations for Enabled Life and Livelihood (FIRE-WELL) program being run jointly between McMaster University and the Hamilton Fire Department (K. Sinden & MacDermid, 2013), as well as the City of Ottawa's "House of Wellness" program (Miller, 2009).

2.2 Firefighter Health and Wellness Interventions

The FIRE-WELL program is a participatory initiative to develop an injury management program for the Hamilton Firefighter's Association in Hamilton, Ontario. Outcomes of the program thus far include a physical demands analysis for firefighting (K. Sinden & MacDermid, 2014) and the implementation of an annual medical screening test for injury risk identification, which includes a critical incident survey, musculoskeletal screening form, and a functional task screen. The team from McMaster University has also conducted research to better understand video observation tools for posture assessment of firefighters (K. E. Sinden & MacDermid, 2016; Chapters 3 and 4 of this dissertation). Although not yet implemented, this research is expected to contribute to the development of ergonomic training programs for the Hamilton Firefighter's Association. Overall, direct impact of the FIRE-WELL efforts on firefighter injury prevention and wellness improvements have yet to be determined given the longitudinal nature of these outcomes; however, anecdotal evidence combined with the dedication of all parties to the project indicates that the initiative has been a success to date (Sinden and MacDermid, 2014).

The "House of Wellness" program, proposed by Dr. Scott Miller to the city of Ottawa, Ontario (Miller, 2009, Figure 1), was based on the recommendation set forth by the International Association of Fire Fighter's (IAFF) Wellness Fitness Initiative (WFI). In this model, Dr. Miller highlights the need for regular medical and fitness evaluations, appropriate injury and medical rehabilitation, behavioural health programs to deal with critical incidents, and the diligent reporting and collecting of data related to each of these program components. Again, results of the adoption of this program have yet to be published; however, evidence of success of similar wellness initiatives in the United States exist (e.g. Elliot et al., 2007; Kuehl et al., 2013; McDonough et al., 2015).

Figure 1: Firefighter's House of Wellness. (Adapted and used with permission from Dr. Scott Miller, http://www.fitasafirefighter.ca/PDF/wellness.pdf, June 2009.)

The PHLAME (Promoting Healthy Lifestyles: Alternative Models' Effects) Firefighter Study (Eilliot et al., 2007), which was conducted on 599 firefighters in the state of Oregon between the years of 2002 and 2004, evaluated two variations of a wellness program. The program focused on health eating habits, regular physical activity, and appropriate body weights. The two interventions tested included: 1) a team-centered, peer-led approach, and 2) an individual counseling with motivational interviewing. Compared against a control group, both interventions showed improved outcomes on fruit and vegetable consumption, body weight, and general well-being. Furthermore, a subsequent study evaluated the economic benefit of the PHLAME Firefighter Program and found that workers' compensation and medical costs decreased in participating firefighters during, and for four years following the intervention (Kuehl et al., 2013). Both interventions also showed returns on investments, with approximate costs per firefighter of $1500 and $600 for the individual and team interventions, respectively, and estimated savings per firefighter of $2765 for each intervention in the four years following the intervention.

More recently, McDonough et al (2015) ran an 8-week "FIT Firefighter" wellness program to encourage healthy behaviour change in a cohort of 29 Mississippi firefighters. Following the intervention, which consisted of nutritional, health, fitness, wellness, and strength and conditioning educational and instructional personal coaching, the firefighters were evaluated based on behaviour change outcomes including motivation, as well as strength, fitness, and physiological outcomes. The results show improvements to each of these outcomes, indicating that providing firefighters with the opportunity to be actively involved in health and fitness programs throughout the year can have a positive effect on health outcomes. Additionally, the authors contend that cognitive awareness alone is not helpful in encouraging healthy behaviours, but rather behaviour change also requires the opportunity, environment, and information needed to work towards those goals.

McDonough et al. (2015) also found that the success of the FIT Firefighter training program led to requests for additional programs including training on safe lifting methods. Indeed, a missing component of each of the programs described above is a concerted effort on ergonomic training. Given the combination of heavy PPE worn by firefighters during fireground operations, the use of equipment that can be heavy and awkward, and with the urgency with which fire suppression tasks often take place, it is important that firefighters not only have a good understanding of safe movement patterns and manual materials handling postures, but also that the use of these safe movements and postures is performed in a relatively automatic way.

2.3 Firefighter Fitness and Movement Training

The heavy physical and cardiovascular demands placed on firefighters given their work tasks, PPE loads, and challenging working conditions invites the title “occupational athletes” to describe this workforce (Figure 2) (Frost et al., 2015). Indeed, elevated levels of physical fitness in firefighters are positively correlated with physical performance assessment scores on occupationally-relevant tasks (Williford et al., 2010). Fitting with the performance improvement and injury prevention rationale of typical athletic training programs, the title of “occupational athlete” has led to the hypothesis that training firefighters in a similar manner to how athletes train in the gym may elicit occupationally-relevant fitness and injury prevention benefits (e.g. Beach et al., 2014; Frost et al., 2015; McGill et al., 2013).

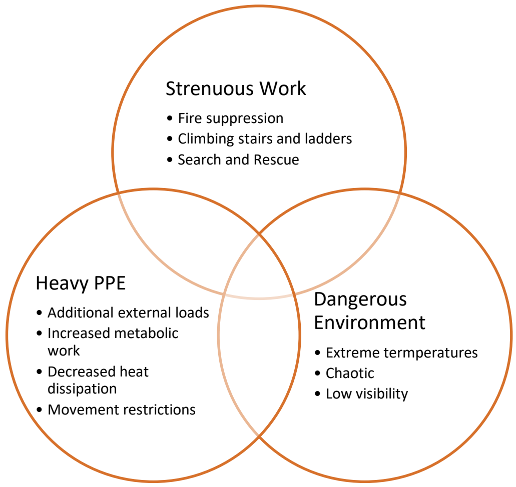

Figure 2: Firefighter job stressors during fireground operations including the type of work, the equipment worn, and the environment. (Adapted from Smith, 2011)

Research out of the University of Waterloo and University of Toronto has explored exercise-based programs to both improve performance and prevent low back injuries in firefighters (Beach et al., 2014; Frost et al., 2015; Frost et al., 2017). This research is influenced by McGill et al. (2013) who concluded that training of firefighters should be augmented by combining traditional fitness objectives with movement competency components. Thus, Beach et al. (2014) and Frost et al., (2015) each evaluated the impact of a 12-week conventional fitness program and a 12-week movement-guided fitness program on overall fitness and low back injury prevention measures. The movement-guided fitness program, which is described by Frost et al. (2012), supplemented the conventional fitness program with appropriate instructions, demonstrations, and feedback to coach participants in adopting the desired postural and motion habits. Beach et al. (2014) determined that both training programs resulted in improved fitness. However, improvements to Functional Movement Scores (FMS), which are used to evaluate the presence of desirable and undesirable movement attributes (Cook et al., 2006a, 2006b; Cook et al., 2010), and measures of occupational low-back loading did not consistently change, which suggests that no injury prevention benefits were gained. However, further investigation of the value of FMS has determined that it may not be an appropriate tool to assess adaptations due to movement-based exercise training (Frost et al., 2017).

Nonetheless, similar to Beach et al. (2014), Frost et al. (2015) found that fitness measures in firefighters improved following 12-week conventional and movement-guided fitness training programs. However, Frost et al. (2015) also show that the fitness program resulted in movement adaptations that put firefighters at greater risk of injury while the movement-guided fitness program led to spine and knee motion improvements suggestive of injury risk reduction during tasks designed to assess the transferability, or motor learning, of the newly acquired movement behaviours to five basic tasks including lifting, squatting, lunging, pushing, and pulling. This latter finding suggests that using a movement-guided approach to fitness training may allow safe and desirable movement patterns to not only be taught, but also to be engrained in motor behaviour such that they can be transferred to occupational activities. As a result, movement-guided fitness training may be a viable solution as a proactive injury prevention strategy for firefighters. However, it is important to note that the transfer tasks, which were not specific fire suppression tasks, did not have the complexity or context of typical fireground tasks. Thus, this research invites the question about how well the movement-guided fitness gains can be transferred to the occupational tasks responsible for firefighter injuries and, furthermore, what the actual injury reduction impact is of these fitness programs. Theories of motor learning may be helpful in answering this question.

2.4 Motor Learning Principles for Movement and Ergonomics Training in Firefighters

Schmidt and Lee (2011) define motor learning as "a set of internal processes associated with practice or experience leading to relatively permanent changes in the capability for a motor skill". Although it is beyond the scope of this thesis to describe the neuro-physiological process by which motor learning occurs, it is important to understand that motor learning is dependent on the brain's neuroplasticity and results in the development of neural connections during the motor learning process (Wulf & Lewthwaite, 2016). As reviewed by Dayan and Cohen (Dayan & Cohen, 2011), these new neural connections make it possible for the acquired skills to be retained over a long period of time, particularly if the training process includes rewards (Abe et al., 2011) and random-order trials (J. B. Shea & Morgan, 1979).

For motor learning to be successful, training programs should be organized in a way that promotes generalization of the learned skills, skill transfer, and long-term retention (Wishart et al., 2000). More specifically, influential factors in motor learning include: observational practice combined with physical practice, having an external focus of attention on the effect of the movement to facilitate motor control automaticity and movement efficiency, feedback for informational and motivational purposes, and self-controlled practice (Wulf et al., 2010). These factors have been incorporated into a new theory of motor learning called the OPTIMAL (Optimizing Performance Through Intrinsic Motivation and Attention for Learning) (Wulf & Lewthwaite, 2016). According to this theory, motor learning occurs because of motivational and attentional factors that contribute to the coupling of goals to actions, and subsequent improved motor performance, through the process of motor learning. More specifically, motor skill learning requires: 1) motivation, 2) learner autonomy, 3) future performance success expectancies, and 4) external focus of attention.

Motivation, particularly intrinsic motivation, is an important factor in optimal learning because humans are driven when a positive outcome is expected to occur (Wulf and Lewaithe, 2016). Expectedly, offering positive feedback that is both personal and normative in nature (i.e. social comparative feedback) in the learning process contributes to this motivation for a positive outcome. When humans are the agents of their own positive outcomes, or have autonomy in this learning process, the success is expected to be greater (Wulf and Lewaithe, 2016). Both outcome expectations and self-efficacy are also important in determining performance success, with positive feedback favourably impacting both, and are therefore required for optimal motor learning. When possible, providing learners with the opportunity to view their own best performances compared to their own average performances, a process known as self-modeling, further improves the learning process (Wulf and Lewaithe, 2016). However, an external focus of attention on movement effects, rather than an internal focus of attention on specific body movements, is well documented in the literature as the optimal motor learning strategy independent of personal factors such as age, ability, and skill level. This is because an external focus of attention promotes automaticity through fast, unconscious, and reflexive control processes (Wulf and Lewaithe, 2016). An external focus of attention has been shown to yield both movement effectiveness (i.e. balance, accuracy, and consistency) and efficiency (i.e. force production, muscle activity, and cardiovascular responses) (Wulf et al., 2013). In fact, one study showed that movement efficiency was improved when the external focus of attention involved focusing on virtual surroundings from a video display while running on a treadmill (Schucker et al., 2009). Thus, it is conceivable that firefighter training, specifically safe movement and task performance, could be achieved using ergonomic tools that incorporate virtual reality technology.

2.5 Virtual reality training for firefighters

Virtual reality technology, when used as a training tool, has shown potential to combine principles of motor learning and neuroplasticity for the optimization of motor performance by offering practice environments that are enriched and individualized (Levin, 2011). Indeed, virtual reality training tools have many positive attributes for important motor learning factors including: 1) observational learning, 2) practice, 3) augmented feedback, and 4) motivation (Levac & Sveistrup, 2014). For observational learning, users can view their own movements, through representative avatars, interacting with objects within the virtual environment. They can also view instructional avatars. Virtual reality tools generally afford abundant, specific, individualized, and goal-oriented practice trials in ecologically valid virtual environments with precise, consistent, and multi-sensory feedback. The virtual reality tool can also offer feedback that is both personalized and social-comparative. Some virtual reality tools may allow for users to interact with other users and engage in competition with them, which can be a source of motivation to use the tool and perform the required motor practice. Indeed, motivation is one of the primary influential factors in motor learning. As reviewed by Levac and Sveistrup (2014), the literature demonstrates that the novelty and interactive nature of virtual reality tools can increase the motivation of learners to engage in practice. Much like non-virtual reality training environments, practice sessions can include goal-oriented tasks; however, virtual reality training environments can also be easily individualized to meet the specific physical and cognitive needs of the user and create optimal learning conditions (Rizzo & Kim, 2005).Virtual reality training environments can also be easily modified to allow users to experience multiple training conditions in relatively quick succession (e.g. a burning vehicle in a farm followed by a burning high-rise apartment building in a metropolitan city), thereby allowing the trainee learn a library of safe postures for a given task that are independent of a single training environment and can therefore be better transferred to new environments. This is particularly important for occupations such as firefighting, where no two calls are likely to be identical. This approach is well aligned with dynamical systems theory, which suggests that movement patterns emerge as a result of self-organization of physical and biological systems (Hamill et al., 1999). Thus, one single “safe” movement strategy neither can, nor should, be taught, but rather safe postures should be selected based on a lower-level, or engrained, understanding of limb coordination, movement-based injury prevention, and an understanding of environmental and task-specific factors and inputs.

The success of virtual reality tools to teach new skills to users for application in real world environments has been demonstrated in several applications including rehabilitation (e.g. Saposnik et al., 2010), surgery (e.g. Seymour et al., 2002), and aircraft inspection (e.g. Vora et al., 2002). In fact, there is even evidence to support the use of virtual reality training tools in the firefighter population. Bliss et al. (Bliss et al., 1997) trained a total of 35 firefighters to navigate through an unfamiliar building using either the building blueprint, virtual reality, or without any training (control). Although no significant differences were observed between the virtual reality and blueprint conditions, both training conditions offered significantly improved navigation than the control condition. With significant advancements in the virtual reality technology over the last fifteen years since the publication of this article, it is expected that the benefits to using virtual reality technology have also increased. Indeed, Williams-Bell et al. (Williams-Bell et al., 2014) recently reviewed the literature related to fire service training using serious games and virtual simulation. Their findings show that virtual reality training tools for firefighters are typically used for instructing team communication and incident command decision making. However, more individualized skills training, particularly as it relates to health and safety, has had limited attention in the realm of virtual reality training tools. New, inexpensive, and innovative video gaming technology, such as the Microsoft Kinect® has the potential to be used for the development of serious games (i.e.

educational video games) for firefighter skills training (Williams-Bell et al., 2014). However, before individualized skills training programs can be developed, a better understanding is needed of the ergonomic issues that should be addressed within these modules. To date, most ergonomic-related research on firefighters has focused on the design and testing of PPE and occupational tools.

2.6 Current State of Firefighter Ergonomics Research

Injury prevention efforts in the firefighter population have focused primarily on overall fitness and wellness factors. Despite the success of many of these programs (e.g. Elliot et al., 2007; Kuehl et al., 2013; McDonough et al., 2015), a missing component of the health and wellness initiatives of many firefighter associations is ergonomic training. Indeed, even the fittest of firefighters can succumb to musculoskeletal injuries if they perform their tasks using poor postures and techniques, or are wearing or using equipment inefficiently. It is well known that poor postures can result in abnormal or excessive loading to regions of the body not designed for such loads, placing them at greater risk of injury (Keyserling et al., 1991; Kumar, 2001). Additional loads caused by tools and/or PPE can further exacerbate these injury risks. Therefore, modifications to PPE, tasks requirements and equipment, and working postures should be considered in any firefighter injury prevention and reduction initiative.

Firefighter PPE is traditionally designed to protect firefighters from the environmental hazards faced daily in their occupation rather than to increase movement efficiency and performance outcomes. For instance, the Occupational Safety and Health Administration

(OSHA) has assigned criteria for firefighter boot manufacturers to ensure a minimal standard of safety for firefighters. These criteria include the requirement for boots to have a slip-resistant outer sole, be water-resistant up to a minimum of 12.7 cm above the heel, and be made with a midsole material that cannot be penetrated by an 8D common nail under 300 pounds of static force (Occupational Safety and Health Standards (1910), 1970). Garner et al. (2013) studied balance effects of two OSHA-approved firefighter boots, one leather and one rubber. The results, which are based on three postural balance assessments occurring before and after two rounds of the Simulated Firefighter Stair Climb, show greater postural instability in firefighters when wearing the rubber boots with fatigue from the Stair Climb test. The increased mass of the rubber boots may be a factor leading in the neuromechanical adaptation differences due to fatigue between the two boot conditions. However, under dynamic conditions, the greater flexing resistance of leather boots has been linked to increased gait instability compared to rubber boots (H. Park, Kim, et al., 2015).

In the case of wearing an SCBA, load distribution, rather than overall mass, may be a more critical factor in reducing the physiological burden (Griefahn et al., 2003). Griefahn et al. (2003) used physiological cardiac strain and subjective mobility assessments to evaluate three SCBA harness and air bottle combinations during simulated rescue work. Two SCBA conditions used a traditional rucksack and air bottle configuration, with manipulations to the air bottle size and mass (A: 15kg, C: 11.7kg). The third SCBA condition used an innovative rucksack and air bottle combination, with a total mass of

13.7kg and lower center of mass over the back. The authors attribute the observed physiological cardiac strain and subjective mobility scores favouring the use of the third configuration to the lower "ergonomically" distributed mass rather than the overall mass of the SCBA unit. Bakri et al. (Bakri et al., 2012) also compared the effect of heavy and light SCBA bottles with two different harnesses on subjective and physiological responses.

Hur et al. (2015) investigated the effects of air bottle design, including bottle weight, height and centre of mass, on firefighter postural control and found that the bottle design, including height and centre of mass, did not effect postural control. The authors hypothesize that any postural benefit from donning an SCBA with a lowered centre of mass resulting from a shorter SCBA bottle was offset by the fact that the centre of mass was also moved further away from the back due to the greater bottle radius associated with the shorter bottle. This posterior shift in SCBA centre of mass would have caused an increase in the destabilizing moment that countered the benefit from the stabilizing moment associated with the lowered centre of mass. However, the use of a heavy SCBA bottle increased both the amount (i.e. excursion) and random movement of postural sway in the medial-lateral direction, but not in the anterior-posterior direction. Previous work by this research team has also shown that SCBA bottle mass affects the gait of firefighters (Park et al., 2010). Specifically, when donning a heavier SCBA bottle, firefighters had greater ground reaction forces in both the anterior-posterior and medial-lateral directions. Additionally, the firefighters were more likely to make contact between their trailing leg and the objects they were trying to step over. The implication of these studies is that the use of heavier SCBA bottles may place firefighters at a greater risk of falls and tripping hazards. However, re-designing the SCBA, including lowering the mass of the SCBA bottles, may reduce these injury risks. More research, however, is needed to evaluate the impact of SCBA dimensions and mass distribution not only on measures of postural stability and mobility, but also on biomechanical loading of the human body.

Although the SCBA and boots have been reported to have the greatest impact on functional balance (Punakallio et al., 2003) and mobility (Park et al., 2015), respectively, bunker, or turnout gear, including the pants, jacket, and gloves worn by firefighters, has also been shown to restrict mobility (Park et al., 2015; Park et al., 2011) and increase physical strain (Neesham-Smith et al., 2014), thereby increasing the risk of musculoskeletal injury. More specifically, wearing full PPE, including bunker gear, boot, helmet and mask, and SCBA, caused a decrease in gait performance characterized by a decrease in speed and step length, and an increase in step width and number of movement errors during an 8m obstacle course (Park et al., 2011). Upgrading from the standard bunker gear (average mass = 11.1kg) to a lighter and less thermally insulated set of gear (average mass = 9.5 kg) had no impact on gait performance. The authors suggest the lack of mobility improvements with the enhanced set of bunker gear may be due to a lack of familiarity with the new bunker gear. However, it is also important to note that a standard SCBA (mass = 9.5 kg) was worn in both conditions, and may have contributed to the maintenance of gait profiles between conditions. Nonetheless, according to a survey of

516 firefighters, (Park & Hahn, 2014), there is clear evidence that fit issues exist with bunker gear that firefighters associate with challenges including movement restriction and functionality. Overall, common fit issues include tightness across the pant legs, misplaced knee pads, and an oversized or stiff neckline. Although the impact of these bunker gear fit issues on injury risk is not well documented, Rosengren et al. (2014) advocate for the importance of developing training programs to educate firefighters about the proper PPE fit and the health and safety risk factors posed by this equipment, with the goal being that increased user awareness may aide in reducing injury risks.

Firefighter injury prevention training programs are also needed to coach firefighters on safe movement patterns during strenuous tasks such as fire suppression tasks. For instance, Rosengren et al. (2014) claimed that firefighters often use asymmetric lifting and carrying strategies during fire suppression tasks, particularly when carrying heavy and awkward materials. Although teaching safe movement patterns is important, a complimentary intervention is to re-design the tasks, where possible. However, in order for such re-design suggestions to occur, a more thorough understanding of the ergonomic challenges with the task are needed. Indeed, Cloutier and Champoux (2000) have stated that: “the task demands of firefighting are not very well known. Only field research can fill this knowledge gap”. There are, however, several ergonomic evaluations of firefighter tasks in the scientific literature.

In 1991, Lusa et al. evaluated the postures of young and old firefighters performing a rescue-clearing task, whereby a 9 kg power saw was lifted from the floor to ceiling level.

Through kinematic and kinetic assessments, the movement speed and peak torques for the knee and back were determined. No differences between young and old firefighters were observed; however, the authors conclude that the tasks involve a high load burden on the musculoskeletal systems of firefighters. The use of proper work techniques was recommended when using heavy manual tools.

Gentzler and Stadler (2010) used a series of common ergonomic tools (i.e. the National Institute of Occupational Safety and Health (NIOSH) lifting equation, the Rapid Entire Body Assessment, and the Rapid Upper Limb Assessment) to conduct ergonomic analyses of current practices for two hose manipulation fireground tasks (Task 1: hose lift above shoulder height for draining, and Task 2: Rolling of drained hose) identified as being high risk to firefighters. The ergonomic analyses indicate that Task 1 is at a "very high" risk level for injury due to raising the hose above shoulder height. Task 2 is at a "high" risk level for injury due to significant trunk bending. By way of solutions, the authors proposed the design and use of hose rollers to reduce the burden on firefighters associated with manual materials handling when draining and rolling hoses following a fire. As next steps, Gentzler and Stadler (2010) then recommend an iterative design and assessment process, whereby the recommended device should undergo ergonomic evaluation to ensure that it does not cause any unforeseen injury risks.

In addition to fireground activities, firefighters are often also responsible for emergency rescue and evacuation activities. Lavender et al. (2015) evaluated the performance and body mechanics of twelve firefighters as they descended three flights of stairs using six difference patient transportation devices (i.e. sleds) that were equipped with a training mannequin. Four of the six sleds (i.e. a fabric mat, a corrugated stretched, a roll-up sled, an inflatable mat, a hard shell sled, and a wheeled sled) required two-people stair descent. The width of the staircase was also manipulated such that there was a narrower (1.12 m) and a wider (1.32 m) staircase. The results show faster performance time when descending the wider staircase. The wheeled sled appeared to be the most physically demanding, with greater erector spinae muscle activation and forward trunk flexion. While a full ergonomic assessment of the tasks was not conducted, the study was in-line with the recommendation by Gentzler and Stadler (2010) to evaluate multiple designs to accomplish a given task. The study results can be used to inform the development of recommendations for the sled style used for high-rise building evacuations. However, more thorough ergonomic evaluations of the tasks are still needed with firefighters donning task-appropriate PPE in order properly assess and reduce the risk of injury to firefighters.

Assessing firefighting tasks using ergonomic tools, much like was done by Gentzler and Stader (2010), allows for new suggestions for injury prevention to be identified. While traditional ergonomic tools can be used to roughly assess the impact of these recommendations from an injury prevention perspective, the proactive use of VE tools for such an application would allow for more comprehensive and accurate assessments to be completed given the level of sophistication of the software and the ease with which realistic simulated environments can be created. Indeed, the challenges in collecting simulated or real fireground operations data may be an important factor in explaining the dearth of ergonomic interventions in firefighting. Additionally, an important consideration when planning an ergonomic training program for firefighters is the fact that there are more volunteer fire departments in Canada than full-time fire departments, where volunteer fire departments may have limited time and resources to run intricate training programs. In Ontario, of the 449 fire departments, 32 are full-time, 226 are volunteer, and 191 are composite departments (MCSCS, 2014). In total, Ontario has 11,367 full-time firefighters, 19,347 volunteer firefighters, and 343 part-time firefighters. However, the limited literature regarding the use of these ergonomic programs in Canada combined with the fact that most Canadian fire departments are rural and staffed largely by volunteer firefighters who have limited time for training suggests that the presence of firefighter wellness programs within Canadian fire departments is likely minimal. Thus, making ergonomic training programs more easily accessible, fun, and less dependent on logistical issues such as classroom bookings and the hiring and training of program coordinators may facilitate more widespread acceptance and adherence to the training programs. VE training for firefighters may be an effective way to teach important injury prevention postures, techniques, and movement strategies to firefighters. However, first, as described above, a better understanding is needed both of firefighter ergonomics as it pertains to the use of common and high risk postures, tasks, and equipment, as well as the contribution of external loads caused by PPE on work-related injury risks. As demonstrated with this dissertation, VE tools may be helpful in gaining this understanding of firefighter injury risks and ergonomic solutions.

3. General Purpose of Dissertation

VE tools have a great deal of utility in assessing musculoskeletal injury risks across many industries. However, improvements to these tools are still needed to ensure that their outputs are valid and that they can account for a diversity of task constraints, including external loads worn by workers such as the PPE worn by firefighters. Indeed, firefighters are a workforce who experience high physical demands and, consequently, are frequently injured. Thus, VE tools may be useful to better understand the injury risk factors and work towards developing solutions that can improve the safety of firefighters.

The motivations behind the work presented in this dissertation are two-fold: 1) to improve VE tools for traditional and novel applications, and 2) to identify injury risk to firefighters during fire suppression tasks.

The accuracy of the final DHM posture ultimately determines the accuracy of the subsequent ergonomic assessment, with small errors in posture potentially having a large impact on injury risk assessment outcomes (Chaffin & Erig, 1991). Current DHM manual manipulation protocols rely on the implicit understanding of human movement strategies by expert ergonomists to accurately posture the DHMs in accordance with their interpretation of how a real worker would perform the given task. However, recent research findings suggest that the use of a set of postural guidelines, even in experienced ergonomists, may improve the accuracy of using DHM manual manipulation for proactively assessing workstation ergonomics in automotive manufacturing (McInnes et al., 2009; Potvin et al., 2008). Chapter 2 investigates the impact of these postural guidelines on DHM manual manipulation accuracy and with the goal of offering recommendations to ergonomists when using VE tools.

Recent technological advancements in software development and motion capture tools mean greater potential of VE tools beyond their typical usage in automotive manufacturing, aerospace, and defense industries. Firefighting, given the high injury rate and nature of the work that makes conducting traditional ergonomic assessments challenging, is an occupation that may benefit from the use of VE tools to better understand and address musculoskeletal injury risks. Chapter 3 of this dissertation uses a traditional video observation approach to better understand the breadth of postures used by firefighters (n = 48) and the subsequent need for ergonomic action during three common fire suppression tasks. The purpose of study was to identify the trends, if any, in posture selection based on firefighter demographics and anthropometrics, the diversity of postures used during different phases of each task, and the need for more in-depth ergonomic assessments. In Chapter 4, a more in-depth ergonomic assessment of high-rise pack lift postures was conducted using a subset of the firefighter data (n = 12) from Chapter 3. Two VE software packages, Jack and 3DSSPP, were used to conduct this in-depth ergonomic assessment, with the Jack assessments using pre-recorded 3D motion capture data from a Microsoft Kinect® system to aide in driving the DHM postures. However, given that protocols do not exist in the scientific literature for using either of these tools for firefighter ergonomics, a primary goal of this research was to determine the strengths, limitations, and opportunities for improvement when using VE tools for the assessment of firefighter ergonomics. First, a method for estimating the external loads caused by the bunker gear and SCBA pack was proposed. Next, an evaluation of ergonomic tool outputs following DHM posturing using each of these two VE software packages was compared and discussed.

This dissertation concludes by summarizing the outcomes and recommendations made in each of the studies and provides insight into how these findings can be used in future directions to both improve general VE protocols as well as reduce firefighter exposure to musculoskeletal injury risks. Specifically, we expect that future work will focus on developing ergonomic training modules using innovative gaming technology to allow for an interactive and engaging training experience for firefighters.

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CHAPTER 2: THE EFFECT OF MANIKIN ANTHROPOMETRICS AND POSTURING GUIDELINES ON PROACTIVE ERGONOMIC ASSESSMENTS USING DIGITAL HUMAN MODELS

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Abstract

Preliminary investigations of the validity of manual digital human model (DHM) manipulations, to accurately reproduce real worker postures, have identified a potential need to refine the manual posturing strategies used by ergonomists when performing proactive virtual ergonomics assessments. This study investigated the effect of altering manikin anthropometrics and implementing posturing guidelines when using DHMs for this purpose. Twelve automotive assembly-line tasks were used to assess the differences between real worker postures, captured via motion capture techniques, and postures obtained from manually manipulated DHMs scaled to either an average female DHM or the real worker average height. Ergonomists performed the DHM assessments using a set of five postural guidelines. Using the postural guidelines generally resulted in more conservative estimates and, in some tasks, improved accuracy across kinetic (% capable, total solved force, L5-S1 compression force, and resultant shoulder torque) and kinematic (shoulder, elbow, and trunk joint angles, and shoulder and L5-S1 reach distances) variables.

Key words: virtual reality, digital human model, proactive ergonomics, anthropometrics, posture, automotive manufacturing

1. Introduction

Virtual ergonomics (VE), where digital human models (DHMs) are manipulated in a virtual environment to simulate real worker tasks and evaluate the corresponding ergonomic issues, has been in practice by several automotive companies to assess assembly-line workstations early in the product design stage. Proactive VE practices attempt to identify potential ergonomic issues even before the workstation physically exists and workers are assigned to their job. This type of ergonomics practice has resulted in substantial decreases in workplace injuries, increased financial gains and improved product quality, particularly in the automotive manufacturing industry (Brazier et al., 2003); however, accurately predicting worker postures in a virtual work simulation, before the task actually physically exists, is an on-going struggle.

Stephens and Godin (2006) reported that the majority of VE assessments for automotive manufacturing at Ford Motor Company were conducted using the "Static Method", where manual manikin joint manipulation (MMJM) of DHMs are used to estimate the final task posture in a virtual environment. At that time, the remaining virtual assessments were performed using motion capture techniques, which are considered to be a more costly but arguably a more accurate method of practicing VE. However, Stephens and Godin (2006) reported a goal of using posture prediction methods for half of future VE assessments, and a greater reliance on motion capture techniques versus the currently dominant static MMJM method. To meet these goals, which are common among most leading ergonomics practitioners, several researchers are attempting to uncover posture prediction algorithms using either statistical modeling or by optimizing/minimizing such things as discomfort (e.g.Yang et al., 2006), energy expenditure (e.g. Kim et al., 2006), fatigue (e.g. Ma et al., 2009), and strength (e.g. Li and Zhang, 2007). However, to date, no algorithm has been shown to accurately predict all postures, especially the awkward postures often required in automotive assembly.

As a result of the current absence of generic and robust posture prediction algorithms, improvements to the more traditional Static method are needed and warranted based on its continued high frequency of usage. Investigations of the validity and reliability of this method, to accurately reproduce real worker postures, have identified a potential need to refine the manual posturing strategies used by ergonomists (Lamkull et al., 2008; McInnes et al., 2009; Potvin et al., 2008). Based on findings by Potvin et al. (2008) and McInnes et al. (2009), it was hypothesized that critical manual posturing guidelines should include:

1) limiting neck extension,

2) maximizing proximity to the object, except during overhead tasks,

3) minimizing trunk and shoulder rotations,

4) being mindful of the installation effort, and

5) maintaining visibility with the part.

Since ergonomists are tasked with ensuring that the majority of the general population can perform a given task, VE practices typically use the anthropometrics of an average female (i.e. 50th percentile female), paired with the acceptable limits of a 25th percentile female strength. This ensures that tasks are designed to be biomechanically acceptable to 75% of females, and most males. To evaluate certain reaching and bending tasks, manikins representing a 5th percentile female and/or a 95th percentile male are also used. However, in order to evaluate the accuracy of manual posturing techniques used by ergonomists when manipulating DHMs, it was hypothesized that postures from real workers and height-matched DHMs should be compared. Thus, the purpose of this study was to investigate the effect of altering manikin anthropometrics and implementing posturing guidelines on postural accuracy when using DHMs for proactive ergonomic assessments.

2. Methods

2.1 Study Overview

The data presented in this study are from two separate data collections (Figure 1), each using the same 12 assembly-line tasks. The first study (S1, Potvin et al. 2008) used:

1) MMJM data from professional ergonomists (i.e. Static method data),

2) motion capture data from real workers (Real) performing the tasks in a virtual environment.

In the second study (S2), the MMJM component of S1 was repeated to evaluate the effect of various posturing guidelines and the use of actual subject anthropometrics.

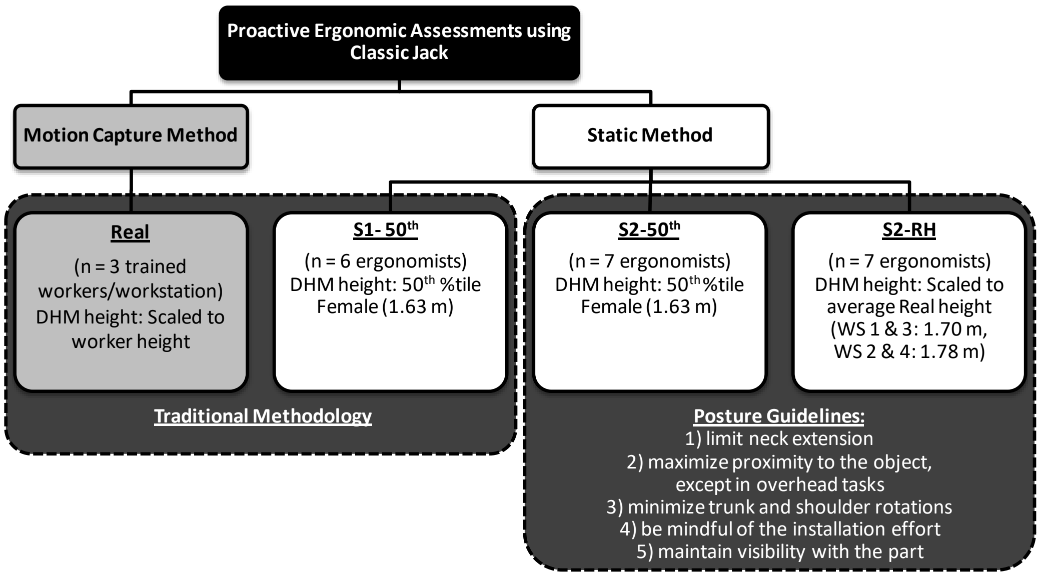

Figure 1: Study design showing methodological differences between data sets, including the posture guidelines assessed.

(Notes: "Real": motion capture methodology was used to the collect posture data from real workers simulating their assembly-line tasks (from Potvin et al., 2008). For the purpose of this study, this method was considered to provide the criterion measures for comparison. "S1-50th": experienced ergonomists performed MMJM of a 50th percentile female manikin, with no specification of the usage of posture guidelines (from Potvin et al., 2008). "S2-50th": experienced ergonomists performed MMJM of a 50th percentile female manikin using posture guidelines. "S2-RH": experienced ergonomists performed

MMJM of a height-scaled manikin using posture guidelines. Manikins were scaled to the average height of the real workers from each workstation (WS).)

2.2 Tasks

Twelve assembly-line tasks (Figure 2) were simulated both virtually using MMJM, and in a laboratory setting using sophisticated props and motion capture techniques. All tasks were selected from automotive assembly-line plants, with six from a larger vehicle in a truck plant and six from a smaller vehicle in a car plant. The six tasks from each plant were selected from two workstations per plant (n = 2 plants x 2 workstations/plant x 3 tasks/workstation = 12 tasks). The selected tasks where chosen from a range of work zones in order to represent a variety of horizontal and vertical reaches (i.e. close reach (3), far reach (3), overhead close reach (3), overhead far reach (3)). Installation efforts for each task were obtained from existing data, or were derived from sampling the on-line efforts using a handheld force gauge.

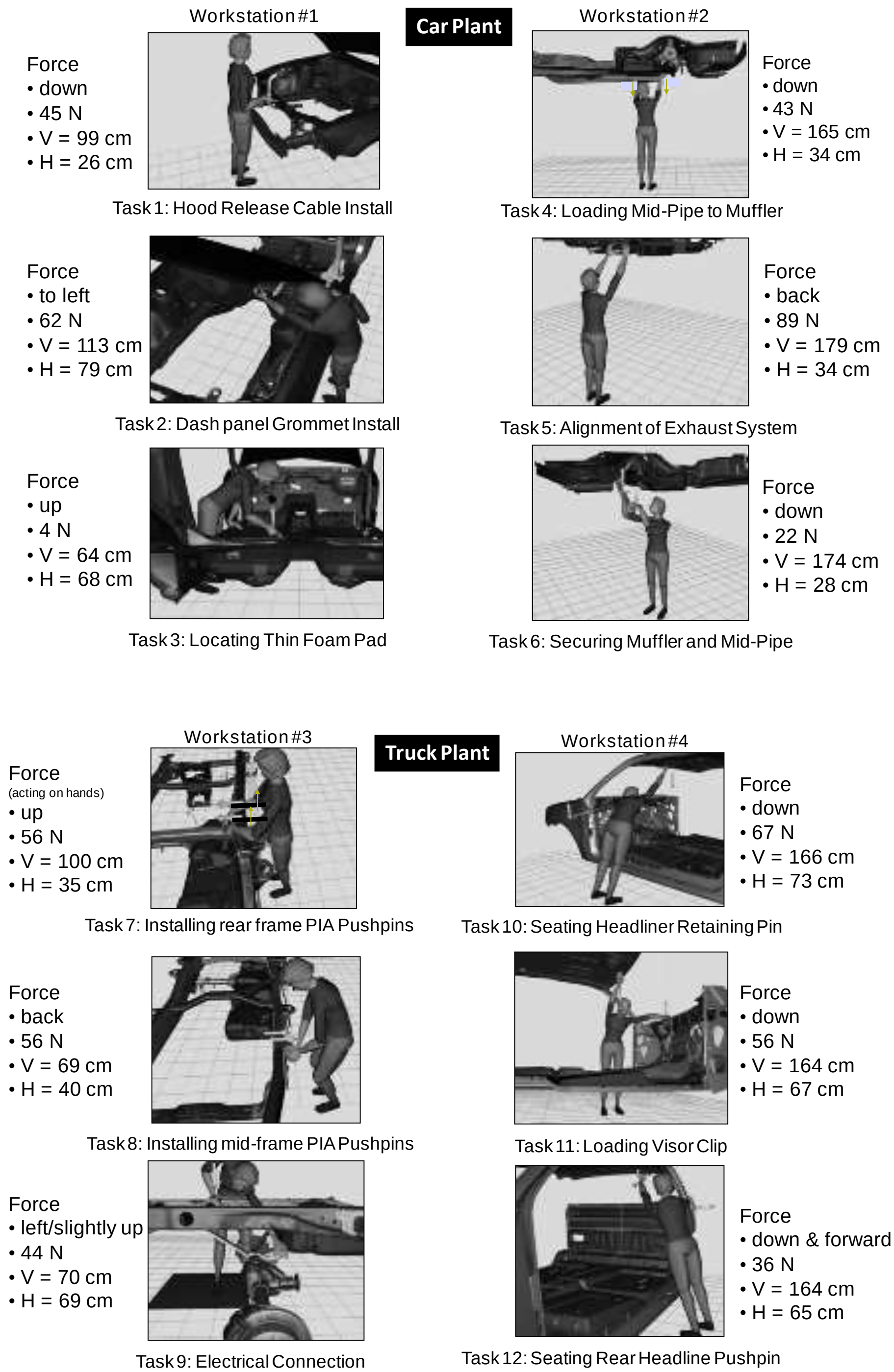

Figure 2: Workstations selected from car and truck assembly-line plants for assessment in the present study (Adapted from Potvin et al., 2008).

2.3 Protocol

Motion Capture Assessments

Three trained "Real" workers, from each of the chosen workstations, were recruited to participate in the Motion Capture portion of S1 (Table 1) (n = 3 workers x 4 workstations = 12 workers). The kinematic data were collected in a motion capture laboratory with an 18 camera system (Hawk cameras, Motion Analysis Corp., Santa Rosa, CA) filming at a rate of 60fps, and physical props (e.g. real vehicle sections and real parts) to replicate the assembly-line workstations (Figure 3). Workers were equipped with a fifty-two reflective marker full-body motion tracking suit. They were asked to replicate three tasks from their own workstation, with video feedback of them performing their task in the actual assembly plant. This was done to ensure that the actual assembly-line postures were replicated and captured in the laboratory simulation.

Table 1: Subject anthropometrics for the Real workers. Subject ages ranged from 25-50 yrs.

			Subjects				
	Workstation	**Tasks**	**S1**	**S2**	**S3**	**Average**	**SD**
Height (m)	**1**	**1-3**	1.70	1.75	1.68	**1.71**	**0.04**
	2	**4-6**	1.73	1.80	1.80	**1.78**	**0.04**
	3	**7-9**	1.65	1.75	1.68	**1.69**	**0.05**
	4	**10-12**	1.70	1.85	1.78	**1.78**	**0.08**
Mass (kg)	**1**	**1-3**	73.2	93.2	68.0	**78.13**	**13.30**
	2	**4-6**	86.4	83.4	84.8	**84.87**	**1.50**
	3	**7-9**	74.3	78.2	70.5	**74.33**	**3.85**
	4	**10-12**	N/A	87.0	75.0	**81.00**	**8.49**
Sex	**1**	**1-3**	M	M	F		
	2	**4-6**	M	M	M		
	3	**7-9**	M	M	M		
	4	**10-12**	M	M	M		

Figure 3: Sample of the process by which an assembly-line task (a), was simulated in a laboratory setting (b). A subject was equipped with a motion tracking suit (i.e. reflective markers) and performed the task as if they were on the assembly-line, with physical props and virtual feedback. The motion data were then streamed into the Jack software (c) where the motion data drive the manikin's movement. The postural data from the manikin are used to assess joint injury risks using ergonomic tools.

Once comfortable with the set-up, workers performed five trials of their respective tasks. Each trial required that the worker enter into the final task posture, and hold that posture for three seconds. The marker data from the final posture were fit to a skeleton using EvaRT (Motion Analysis Corp.), which was streamed into the Classic Jack Software (v 5.0, Siemens PLM, Plano, TX) and superimposed onto a manikin within the software. Once this was achieved, a frame representing the posture during the brief forceful effort was selected for analysis. For each Real Worker subject, the Jack manikin was scaled to their own actual height, similar to the static assessments, but the subsequent analysis assumed that the manikins had the mass of a 50th percentile female. Note that all Real workers tended to be taller than the female average of 1.63 cm, and that those from the overhead tasks in Workstations 2 and 4 were an average of 7-8 cm taller than those from Workstations 1 and 3.

Static Ergonomic Assessments

Six professional ergonomists for S1 (3 males, 3 females, age: 33.82 ± 6.02, years experience: 1.39 ± 1.12), and seven professional ergonomists for S2 (5 males, 2 females, age: 35.00 ± 6.61, years experience: 3.17 ± 3.89) were used as subjects and performed the 12 MMJM assessments using Classic Jack Software (v 5.1 for S1 and v6.0.1 for S2). None of the subjects participated in both S1 and S2. All subjects were experienced with Classic Jack, and with conducting static ergonomic assessments.

Each subject performed static ergonomic assessments of all 12 tasks. In S1, three repeat trials were performed, each a week apart, for a total of 36 trials per subject. In S2, two trials were performed for each task, each with a different manikin, with a week between each block of trials, for a total of 24 trials per subject. In both studies, the task order was presented randomly for a given block of trials.

To complete each assessment, subjects were provided with CAD/CAM data of the workstation and vehicle objects and layout. Each subject was given a set of work instructions that provided a description of each task, the installation effort in Newtons, effort locations, number of hands to use, tools to be used, visual requirements etc. For example, for Task 1 (hood release cable install), the task was described as follows: “This task simulates the install of the hood release cable to the radiator support. In this task a split clip is installed over the hood release cable. The cable is routed with two hands and then the clip is inserted through a hole in the sheet metal tab from the bottom up with one hand (45 N). The hole location is marked by a centroid." General instructions for all workstations were also provided. For both S1 and S2, subjects were asked to proactively estimate realistic postures that real operators would eventually use to perform the task and to avoid collisions between the manikin and the vehicle. Additional more specific instructions were provided for S2, and included:

1) limit neck extension,

2) maximize proximity to the object without extending the neck,

3) minimize trunk and shoulder rotations,

4) be mindful of the installation effort,

5) maintain visibility with the part.

Given these instructions, subjects were required to manually manipulate their respective manikins in a 3-D virtual rendering of the real tasks. For all S1 assessments (S1-50th), and for one set of S2 assessments (S2-50th), a 50th percentile female DHM height of 1.63 m was used. The second set of assessments in S2 used anthropometry that matched that of the average Real worker heights (S2-RH), which were 1.70 m for Workstations 1 and 3, and 1.78 m for Workstations 2 and 4. A 50th percentile female mass of 61.25 kg was used for all S1 and S2 assessments.

2.4 Data analysis and dependent variables

Kinetic and kinematic data (Table 2) from each of the final postures, for all trials achieved either through manual DHM manipulation or Motion Capture, were output using the Ford Ergonomics Static Strength Prediction Solver (FSSPS) (Chiang et al., 2006). The FSSPS records joint angles, torques, strengths, and strength percent capable (%Cap) for various joints based on the known hand loads, from the Classic Jack software, and, if present, external support requirements. Based on the %Cap, the task may be deemed "acceptable" or "unacceptable" to 75 % of females, which is a standard used to ensure that most of the working population can perform a given task. Additionally, FSSPS calculated the Total Solved Force (TSF), which is the maximum hand load acceptable to 75% of females.

Kinetic dependent variables included: TSF, resultant shoulder torque, L5/S1 compression force and the %Cap values for the elbow (flexion), shoulder (abduction/adduction, forward/backward, and humeral rotation axes) and trunk (flexion, lateral bend, and axial twist axes). The resultant shoulder torque was calculated using joint torques from all three shoulder axes, and was determined to be the higher value of the left and right shoulders. The limiting %Cap value for each joint was selected to represent the %Cap of that joint, and the limiting %Cap of all the joints was selected as the Total %Cap (T%C).

Kinematic dependent variables included: the joint angles at the elbow (flexion), shoulder (abduction/adduction, forward/backward, and humeral rotation axes) and trunk (flexion, lateral bend, and axial twist axes at L5/S1). When two hands were used for a task, a weighted joint angle value was calculated based on the proportion of total task force that each hand exerted. For example, if the left and right hands used 20N and 30N of force respectively, then the weighted elbow joint angle would the sum of 40% left elbow angle and 60% of the right elbow angle. The horizontal reach distance, from L5/S1 to the hand, was also calculated for each task. When only one hand was used to perform the task, the L5/S1-to-hand horizontal reach distance was calculated only for that side of the body. When both hands were used to perform the task, the average distance was calculated between each of the left and right sides of the body.

Table 2: List of kinetic and kinematic dependent variables calculated.

Kinetic Variables	**Kinematic Variables**
Total Solved Force (TSF)	Weighted Elbow Joint Angle in the flexion axis
Resultant Shoulder Torque	Weighted Shoulder Joint Angle in abduction/adduction, forward/backward, and humeral rotation axes)
L5/S1 Compression Force	Weighted Trunk Angle (at L5/S1) in flexion, lateral bend, and axial twist axes
Elbow % Capable (Elbow %Cap) in the flexion axis	Weighted Resultant Shoulder Angle
Shoulder % Capable (Shoulder %Cap) in abduction/adduction, forward/backward, and humeral rotation axes)	Weighted L5/S1-to-Hand Horizontal Reach (averaged between loaded sides)
Trunk % Capable (Trunk %Cap) in flexion, lateral bend, and axial twist axes	
Total % Capable (T%C)	

2.5 Statistical analysis

A Mann-Whitney test, which can be performed without the requirement of normally distributed samples, was used to test for differences in age and experience between the independent groups of ergonomists that were selected for S1 and S2. (Note: no ergonomist participated in both S1 and S2.)

For each of the dependent variables, between-subject means and standard deviations were calculated for each Task/Method combination. A two-way analysis of variance (ANOVA) was used to test for the effects of Method ($n = 4$) and Task ($n = 12$) for TSF, T%C, and each of the kinematic variables ($\alpha = 0.05$). A Tukey's post-hoc analysis was used to further explore differences between methods.

In order to gain a better understanding of the absolute errors of each static assessment method compared to the Real worker postures, the Tasks were also examined individually and after being grouped by work zone (i.e. close reach, forward reach, overhead close reach, and overhead far reach) using a root mean squared error (RMSE) analysis. To do this, RMSE was calculated between each static assessment method and the values from the Real workers in two ways:

1) within work zones,

2) averaged across all tasks.

It is important to note that the RMSE method allows us to determine which methods reduce the error between the manual manipulation of DHMs and Real worker postures. However, while a lower RMSE is indicative of an improved estimate of the Real posture, this analysis method does not account for the direction of the error, which is an important consideration in order to avoid inappropriately calling a task acceptable. Therefore, descriptive statistics were also used to compare the mean value for each dependent variable, and for each task, across each of the ergonomic assessment methods.

3. Results

No significant differences were found in age ($p = 0.836$) or years of experience ($p = 0.366$) between the samples of professional ergonomists selected for S1 and S2.

The results of the ANOVA show interaction effects between Method and Task for TSF and across all kinematic variables tested (Table 3). A main effect for Task was found for T%C. The post-hoc analysis shows no differences across variables tested between the S1-50th and S2-50th methods. In comparison to the other three methods, the Real method had smaller overall mean shoulder abduction angle and resultant shoulder angle, and greater overall mean trunk flexion angle (Table 4). The Real method was also different from the S1-50th method for overall mean TSF, with a smaller TSF being recorded in the Real method, but this difference was not seen in the comparison between Real and the S2 Methods. The S1-50th vs. S2-RH and S2-50th vs. S2-RH comparisons showed differences in overall mean elbow flexion angle (greater angles for S2-RH) and shoulder abduction angle (smaller angles for S2-RH), with differences in overall mean resultant shoulder angle only being observed for the S1-50th vs. S2-RH comparison (smaller angles S2-RH).

Table 3: Results of the analysis of variance for the TSF, T%C, and the kinematic variables. (* denotes a significant finding, p<0.05)

	Total Solved Force	Total % Capable	Elbow Flexion Angle	Shoulder Abduction Angle	Shoulder Flexion Angle	Resultant Shoulder Angle	Trunk Flexion Angle	Trunk Bend Angle
Method	0.0140*	0.4878	0.0010*	0.0010*	0.0968	0.0010*	0.0010*	0.0794
Task	0.0001*	0.0001*	0.0010*	0.0010*	0.0010*	0.0010*	0.0010*	0.0010*
Method * Task	0.0015*	0.2812	0.0015*	0.0010*	0.0218*	0.0010*	0.0345*	0.0010*

Table 4: Mean values and standard deviations for each dependent variable tested in the ANOVA for each Method across all Tasks.

Method	Total Solved Force (N)	Total % Capable (%)	Elbow Flexion Angle (degrees)	Shoulder Abduction Angle (degrees)	Shoulder Flexion Angle (degrees)	Resultant Shoulder Angle (degrees)	Trunk Flexion Angle (degrees)	Trunk Bend Angle (degrees)
Real	43.0(18.7)	60.3(28.3)	41.4(29.2)	85.6(32.1)	65.8(19.6)	112.1(25.2)	84.5(20.7)	-1.4(11.3)
S1-50th	53.5(23.2)	64.9(27.9)	35.4(31.6)	103.8(49.2)	69.0(31.0)	134.1(38.0)	69.5(25.0)	-2.5(12.6)
S2-50th	47.9(25.1)	61.1(30.1)	32.5(30.6)	105.8(49.2)	64.4(33.3)	131.6(41.0)	73.6(22.0)	-1.9(11.5)
S2-RH	47.0(24.3)	61.4(29.7)	44.8(35.1)	95.3(46.0)	73.6(29.5)	126.9(38.5)	71.1(21.6)	1.0(12.8)

When the data were examined from a more descriptive perspective, the S1-50th method resulted in T%C values that were generally higher than the Real values (Figure 4). In contrast, the two S2 methods showed more conservative estimates of T%C than the S1-50th method and, in most cases, than results from the Real workers. However, these improvements with the S2 method were observed primarily in non-overhead tasks. The TSF outputs showed similar trends to the T%C (Figure 5). In both measures, smaller overall RMSEs were observed with the S2-RH in comparison to the S2-50th method (T%C: S2-50th=12.2 % versus S2-RH=10.7 %, TSF: S2-50th=19.3 % versus S2-RH=18.4 %).

Other kinetic variables showing a decrease in overall RMSE, between the Real data and Static methods, as a result of the posture guidelines and manikin scaling include: Resultant Shoulder Torque (S1-50th=5.7 % > S2-50th=5.3 % > S2-RH=4.0 %), and L5-S1 Compression Force (S1-50th=473 N > S2-50th=377 N > S2-RH=286 N). These results also show improvements in using the height-scaled manikin, rather than a 50th percentile manikin, when posture guidelines are used for both methods. However, the RMSE for individual joint %Cap showed no trends when examined between work zones.

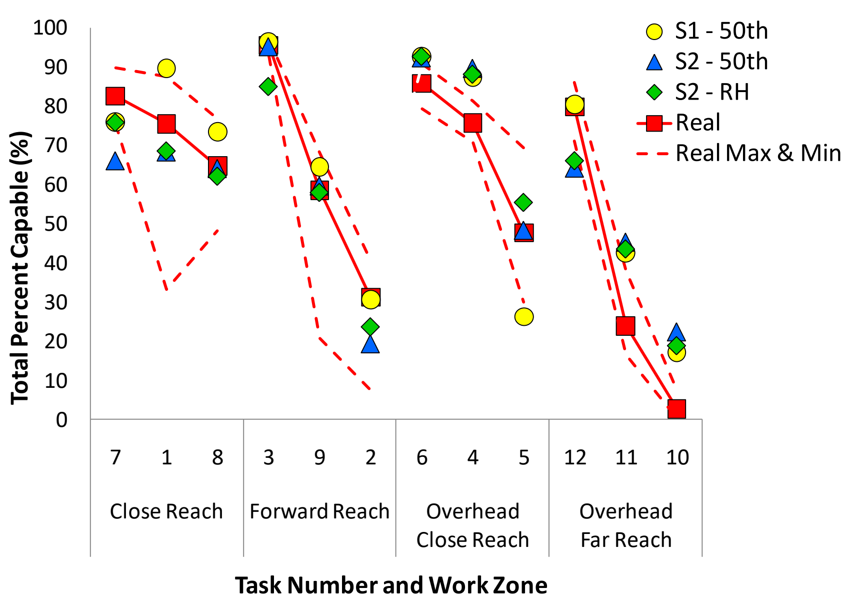

Figure 4: The average Total Percent Capable (T%C) for each assessment method by task location and number.

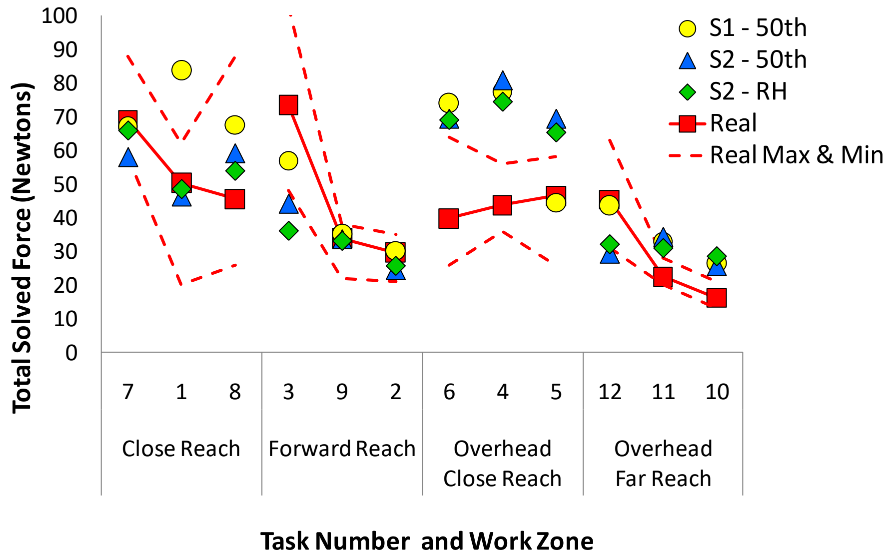

Figure 5: The average Total Solved Force (TSF) for each assessment method by task location and number.

The kinetic findings are supported by the kinematic findings. RMSE, across the 12 tasks, was used to assess the accuracy of the weighted elbow, weighted resultant shoulder, and trunk angles of the manually manipulated DMHs compared to S1-Real data (Figure 6). Improvements in posture prediction were obtained for all joints by implementing the posture guidelines, and were further improved when using the height-scaled DHM (Overall RMSE compared to Real: S1-50 = 22.5 %, S2-50 = 21.8 %, S2-RH = 18.3 %). When examined across work zones, both the S1-50^{th} and S2 methods in the overhead tasks had greater deviations from the Real worker values than for non-overhead tasks for the weighted resultant shoulder (Figure 7). Results for the weighted elbow, trunk flexion, and trunk lateral bend angles showed the same trends. However, improvements were observed with the S2 methods compared to the S1-50th, particularly in the overhead reach tasks for the weighted elbow (S2-RH) and trunk angles (S2-RH and S2-50th).

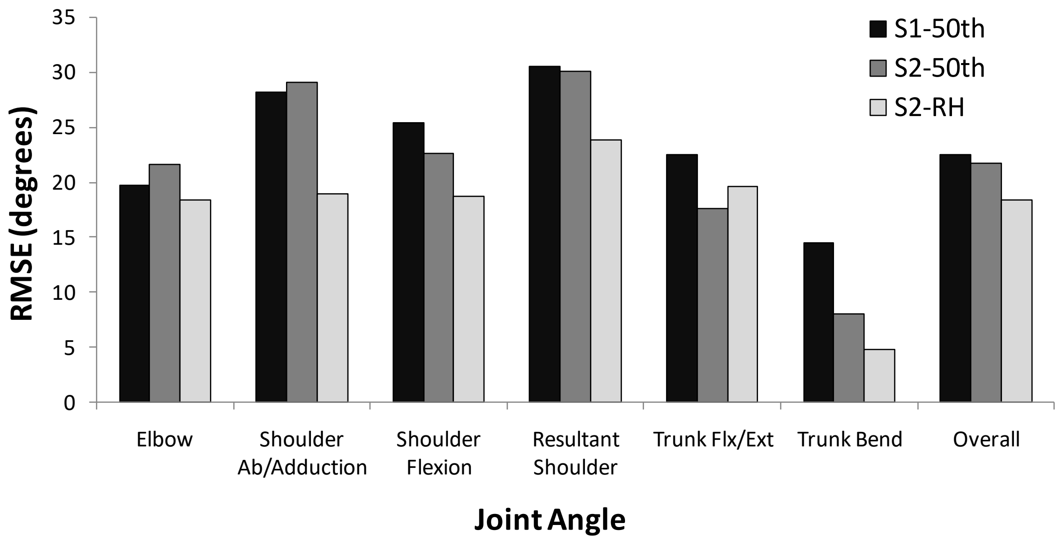

Figure 6: Root mean squared error between all tasks of each static assessment method in comparison to the results from the Real workers for the elbow, shoulder, trunk, and overall joint angles.

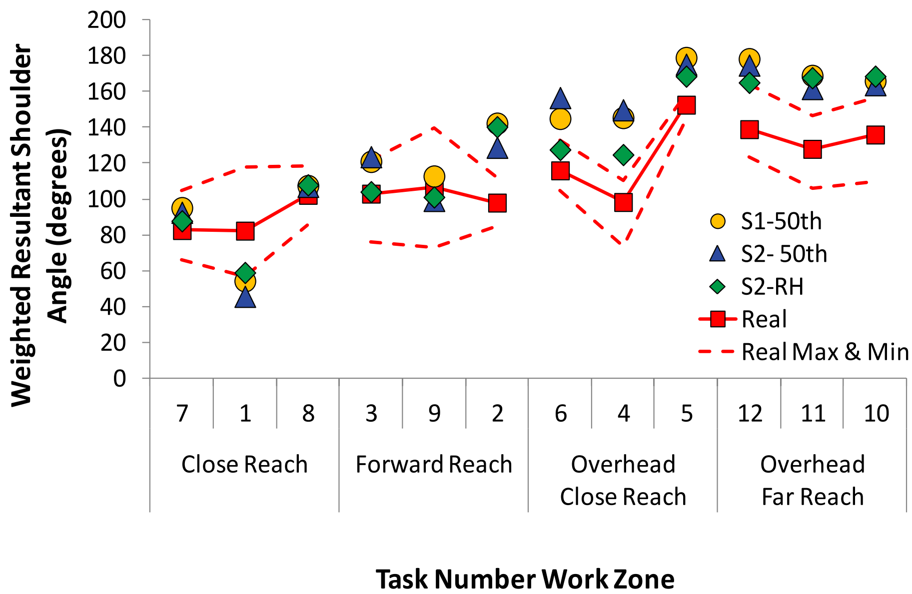

Figure 7: Average with-in group joint angles by work zone and task for the weighted resultant shoulder angle.

An analysis of the L5/S1-to-hand horizontal reach distance show no improvements in overall RMSE between the S1-50th and S2-50th method, but an improvement in horizontal reach with the S2-RH method (Figure 8a). When the analysis was broken down by work zone, the improvements in horizontal reach for the S2-RH method, in comparison to the other Static methods, are most notable in the overhead tasks. Additionally, the S2-50th method shows reduced RMSE compared to the S1-50th method in tasks performed below shoulder height. Overall, for all three Static methods (i.e. S1-50th, S2-50th, S2-RH), there was a decrease in RMSE for tasks requiring reaching both in below-shoulder and overhead tasks (RMSE Forward Reach < Close Reach, and Overhead Far Reach < Overhead Close Reach). The descriptive statistics show a consistent under-estimation of reach distances across Static methods across all tasks, with greater accuracy observed with the S2-RH method (Figure 8b).

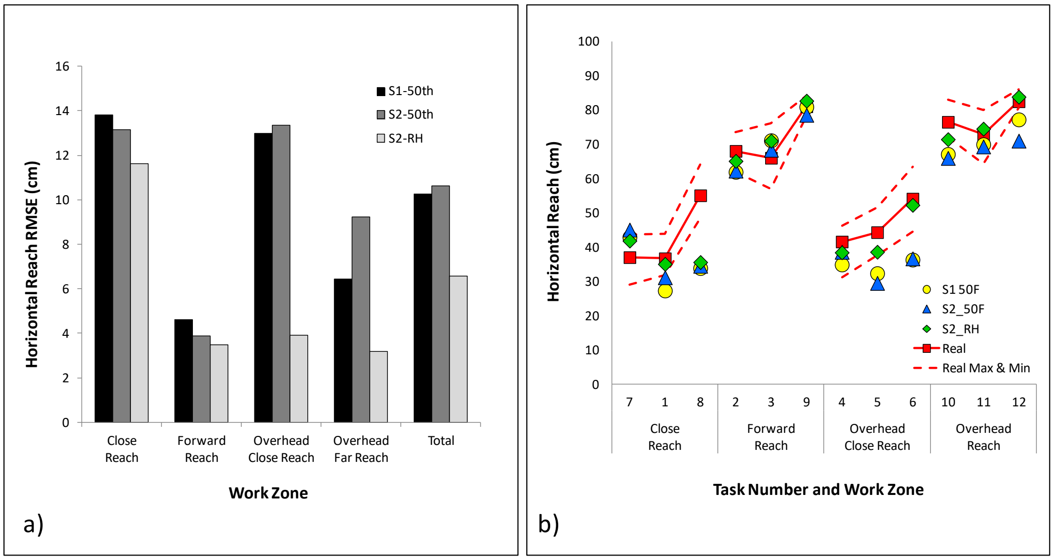

Figure 8: The weighted L5/S1-to-hand horizontal reach distance analyzed using: a) the RMSE calculated between each of the Static methods and the results from the Real workers averaged within each work zone and across all tasks (i.e. Total) and, b) the mean horizontal reach distance for each method, grouped by task and work zone.

4. Discussion

Overall, the results of the ANOVA demonstrate an interaction effect of Method and Task for the variables tested, with the exception of T%C, highlighting that MMJM is dependent on several variables including task location, posturing guidelines, and manikin anthropometrics. By virtue of the tasks being selected to represent the diversity of task locations, exertion force magnitude, and exertion force direction, we expected to find differences between tasks for the variables tested. Thus, for the purpose of this study, the most important findings were the differences in dependent variables between methods. Interestingly, no statistical differences were observed between the S1-50th and S2-50th methods across all variables tested. This finding, combined with the fact that differences were observed between all other combinations of methods, suggests that manikin anthropometrics may be more sensitive than posture guidelines when trying to realistically posture manikins. Furthermore, the shoulder joint, specifically the shoulder abduction angle and the resultant shoulder angle, were the two variables most frequently different between methods, while the trunk flexion angle was consistently different during comparison between only the Real worker method and each of the static assessment methods. These findings highlight the sensitivity of each of the methods and manipulations (e.g. posture guidelines and manikin height) to the resultant manikin postures.

It is interesting to note that no main or interaction effects of Method were observed in the T%C. While this is an important variable in identifying the acceptability of a task, it is also a more conservative variable in comparison to the other variables tested in that it is derived from the most limiting %Cap of all the joints. For this reason, we were also interested in the descriptive statistics so that we can better identify the trends in the data, and the conditions under which the study manipulations improve the manikin postures in comparison to Real worker postures.

Moreover, in the context of this study, the use of an ANOVA had several limitations, which further necessitate the use of additional analysis methods. Firstly, the ANOVA had the potential to average out important deviations in the data thereby introducing a type II error. Additionally, the small sample size tested, particularly for the Real workers, may have further introduced type II errors. For this reason, descriptive statistics and RMSE were also used to describe trends in the data and identify the conditions under which the greatest errors and improvements in manikin posturing are occurring.

As shown in Figure 1, the results demonstrated improved MMJM posturing using the posturing guidelines from the S2 methodology. Further, overall improvements in both kinetic and kinematic variables were observed when the postural guidelines were used in conjunction with a height-scaled manikin (S2-RH) versus a standard 50th percentile female manikin (S2-50th). The greatest postural improvements using the S2 methodology were noted in the non-overhead tasks. Minimal, if any, postural improvements were observed with the S2 results in the overhead tasks. Overall, the use of the posturing guidelines did not yield results that were less acceptable than those reported using the original Static methodology (i.e. S1-50th). Therefore, the results support the continued use of 50th percentile female manikins, when the real worker heights are not known, for proactive ergonomic assessments using DHMs in conjunction with the implementation of the posturing guidelines from the S2 methodology.

The two new methods (S2-50th and S2-RH) offered results that follow similar trends relative to the results from the Real workers. Thus, it can be assumed that the more conservative T%C and TSF values observed are due primarily to the newly implemented posturing guidelines, rather than the manikin anthropometrics. However, the S2-RH method resulted in small overall improvements in several of the dependent variables (T%C, TSF, L5-S1 Compression, Trunk %Cap, Resultant Shoulder Torque, and all calculated joint angles and reach distances). This finding suggests that anthropometrics alter the posturing strategies used by ergonomists when using MMJM for ergonomic assessments. This is an important consideration in proactive ergonomic practices because it suggests that using real worker anthropometrics improves the validity of the assessments. However, given the proactive nature of these types of assessments, and the fact that real-worker anthropometrics are not known at such an early stage of product development, it is impossible to conduct these ergonomic assessments with real worker anthropometrics. Given that only small improvements in accuracy were obtained in S2-RH, it can be concluded that sufficiently accurate postures will be obtained when using a 50^{th} percentile female if the posturing guidelines are adhered to. Additionally, using a 50^{th} percentile female generally yields more conservative results in % Capable and TSF values, thereby ensuring that a larger percentage of the population can safely perform the task. Therefore, the use of the S2-50^{th} method is preferable for general proactive ergonomics practices.

Several limitations exist within this study. First, a relatively small sample size of professional ergonomists was used in both studies and few real workers were recruited for the Motion Capture study. The ergonomists were selected from a company that is a leading user of this type of technology for their proactive ergonomic assessments of assembly-line workstations. Therefore, their ergonomists are some of the most experienced users of this technology. Aside from recording the level of experience, the skill level of each ergonomist is difficult to quantify due to a lack of tool-specific standards. However, in the present study, all ergonomists had at least 4 months of experience in using DHM technology. As recommended by Lamkull et al. (2008), it is important for DHM tool users in the automotive manufacturing industry to have acquired knowledge through plant visits and/or involvement with assembly workers, and to exchange experiences and knowledge with fellow DHM tool users. Over the course of the minimum four-month period, the ergonomists would have benefited from these opportunities; thereby developing at least a base level of knowledge and experience in DHM tool use. Recruitment outside of this sample population may have influenced the results by including subjects with differing backgrounds, aptitudes for DHM technology, applied usage, and experience in the automotive manufacturing industry. Thus, a more heterogeneous sample of ergonomists or DHM tool users may have also confounded the results. However, future research should investigate the importance of technical background, training, and experience in MMJM accuracy. With these limitations in mind, it should be noted that the sample number used in the present study is of similar or greater magnitude to those reported in other studies where ergonomists were recruited to perform virtual assessments using MMJM (e.g. Lamkull et al., 2009, (n=6); Fritzsche et al., 2010, (n=2)).

With respect to the Real workers, each assembly plant only has a few workers that are skilled on a given workstation. In order to ensure that the Real postures obtained with motion capture were from highly trained real workers, it was not possible to select a larger sample population. For this reason, only three workers for each workstation were selected. However, it is recognized that a greater understanding of the posture variation between workers would have been obtained with a larger Real worker sample population. Furthermore, eleven of the twelve workers selected were male. This unintentional selection bias was a function of the sex distribution of the manufacturing tasks that were selected for analysis. While sex-related differences in movement patterns may exist, and may therefore need to be considered when using MMJM to predict postures, such an investigation was beyond the scope of the present study.

With respect to the posturing guidelines recommended in the current study, we could not explicitly identify which guideline had the most influence on the postures obtained after MMJM. It was expected that the guidelines would complement one-another, and therefore would need to be implemented together. For example, for overhead tasks, limiting neck extension was expected to be an important guideline, but so too was maximizing proximity to the object, which workers appear to do in order to minimize shoulder moments. However, in order to maintain visibility with the part, being further from the object would allow for minimizing neck extension. Therefore, by implementing the posture guidelines as a package, ergonomists are free to determine the best combination of factors including; neck extension, object proximity, and shoulder rotation angles. However, we recognize the need to also examine the benefits of each of the posture guidelines independently. To achieve this, a series of controlled studies is planned to assess postures and loading at the neck and shoulder complexes during various constrained and self-selected reaching tasks.

Future work will look at the effect of exertion efforts on MMJM strategies, which have been shown to be poorly estimated by ergonomists (Fritzsche et al. 2010). Real workers adopt different posturing strategies depending on the effort requirements to complete a given task, and that these posturing strategies change depending on the task location and force direction (Hoffman et al., 2007; Hoffman, 2008). However, it is hypothesized that ergonomists do not take into account these effort, task location, and force direction specific posturing strategies when using MMJM, likely because they are either: 1) not sufficiently trained in, or aware of, postural adaptations that are required during changing exertion demands or 2) because they cannot physically simulate the tasks themselves in an environment where haptic feedback is provided, which would allow for a better understanding of the postural requirements for a given task (as reviewed in Stanney et al. 1998). The current data set will serve as a preliminary database for assessing effort-specific errors between the MMJM method and real worker postures. However, additional data will also be collected to better understand the effect of effort requirements, task location, and force direction on real worker posturing strategies, specifically in overhead and reaching tasks where there is currently a relative dearth of postural data.

In conclusion, while good success has been achieved with proactive virtual ergonomic practices using the MMJM methodology, improvements in MMJM strategies and protocols will allow for more realistic postures to be assessed with the current virtual ergonomic tools. We expect the outcome of this to be a better use of available ergonomic and DHM technology. More specifically, this study suggests methods for more realistically manually posturing DHMs for proactive ergonomic assessments, including the implementation of posturing guidelines and altering manikin anthropometrics. By adopting these recommendations, we expect to see more accurate ergonomic assessments for some tasks. It is important to note that limited improvements were observed in the overhead tasks when using the postural guidelines. This finding supports the fact that more work is needed to understand the posturing strategies of overhead tasks, where the neck and shoulder complexes are stressed, finding external support may be a higher priority for the worker, and line-of-sight may be compromised.

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CHAPTER 3: POSTURE EVALUATION OF FIREFIGHTERS DURING SIMULATED FIRE SUPPRESSION TASKS

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Abstract

Posture mechanics during fire suppression tasks are associated with musculoskeletal injuries in firefighters. This study uses the OWAS ergonomic tool to describe and evaluate postures used by forty-eight firefighters during three simulated firefighting tasks: 1) hose drag, 2) hose pull, and 3) high-rise pack lift. Ergonomic intervention prioritizations based on the OWAS Action Classification (AC) scores were identified using Wilcoxon Signed Ranks Tests. Chi-squared analyses identified associations between firefighter characteristics and OWAS AC scores. The initial hose pick-up phase of each task were identified as equally high priority for ergonomic intervention (OWAS AC = 4) in 45.8 %, 54.2 %, and 45.8 % of cases for Tasks 1, 2, and 3, respectively. Lower BMI was associated with higher AC scores for the initial hose pick-up of Task 3 (Likelihood Ratio = 9.20, p-value = 0.01). The results provide information for ergonomic training program content and prioritization based on the tasks studied.

Keywords: firefighters, ergonomics, posture analysis, OWAS

Highlights:

- Firefighters frequently use postures during simulated fire suppression tasks, such as picking up a hose, that put them at risk of musculoskeletal injury.
- Ergonomic training is needed to educate firefighters to safely perform fire suppression tasks.

- Associations between estimated injury risk and firefighter characteristics were not found. As such, tailoring ergonomic training programs based on anthropometric or demographic characteristics may not be needed.

1. Introduction

Firefighting is an occupation that carries many risks related both to the dangers associated with the environment in which they work and to the physical demands of the job. In the United States, data from 2006-2008 show that overexertion and strain were the leading cause of injury (24.9 %) to firefighters, with most of these injuries occurring in the upper extremities (21.6 %) and lower extremities (19.6 %) in firefighters between the ages of 35-39 (U.S. Department of Homeland Security, 2011). Most of these injuries occurred either outside (50.4 %) or inside (44.6 %) the structure under fire, with fire suppression and suppression support activities accounting for 50.7 % and 24.9 % of injuries, respectively.

A recent study conducted on firefighters in Calgary, Alberta, Canada indicated that sprains and strains to the back, knee, and shoulder regions account for 32.1 %, 22.6 %, and 14.5 % of firefighter injuries within the city (Frost et al., 2016). Motion patterns causing these injuries included: 1) bending, lifting, and/or squatting, 2) slipping, tripping, and/or falling, 3) lunging and/or stepping, and 4) exercise and/or training activities. Interestingly, most of these injuries were reported to occur at the station (30.8 %) or training site (27.7 %), rather than during fire (18.2 %) or non-fire (18.2 %) emergency calls.

In Ontario, firefighters and police officers, who are grouped together for statistical purposes by the provinces Workplace Safety and Insurance Board (WSIB), are one of the leading occupations for lost-time claims for self-insured (Schedule 2) employers (WSIB, 2016). Most of these injuries were sprains and strains sustained by male firefighters and police officers between the ages of 40-44. The legs (27.2 % of injuries) are the most frequently reported site of injury, followed by the back (19.2 %) and upper extremity (17.0 %) (WSIB, 2016). Previous analysis demonstrated that a cohort of full-duty firefighters from the Hamilton (Ontario) Firefighters Association (n = 43) most frequently experienced pain in their backs, knees, and shoulders at rates of 39 %, 38 %, and 32 %, respectively (Kajaks and MacDermid, 2015). This high prevalence of musculoskeletal injury and pain in firefighters indicates that further strategies to prevent injury are needed. Injuries sustained during typical firefighting tasks can be reduced by re-designing the tasks (Lavender et al., 2015) or improving personal protective equipment (e.g. Park et al., 2015; Park & Hahn, 2014; Park, et al., 2015; Turner et al., 2010) . However, there is also a need to ensure firefighters have the training and physical attributes necessary to perform their tasks in the safest way possible (Walker et al., 2014). In recent years, there have been legislative efforts on the part of firefighter associations to ensure that firefighter candidates pass rigorous pre-employment entrance exams, such as the Canadian Physical Assessment Test (CPAT), that help ensure that appropriate job fitness is met at the time of hire. For currently employed firefighters, health and fitness maintenance guidelines

(Michaelides et al., 2008) and wellness programs (IAFF, 1997) are available through many North American firefighter associations to help promote healthy lifestyles and workplace safety. Unfortunately, poor health and fitness can result in sub-standard job performance, which is a serious concern with respect to the health and safety of the community, as well as place firefighters at greater risk of sustaining injuries and illness (Poplin et al., 2016). Poplin et al. (2016) showed firefighters who had a low comprehensive fitness score, which was based on cardiovascular fitness, endurance, flexibility, muscular strength and body composition, were at greater risk of injury compared to their more fit counterparts. Interestingly, younger firefighters who were less fit had a greater injury risk than older colleagues, but this relationship was inferred to result more from task requirements and hazard profile associated with this occupation than physiological reasons. Lett and McGill (2006) demonstrated that years of experience as a firefighter contributed to less spinal compression and shearing forces during pushing and pulling tasks. However, Katsavoumi et al. (2014) found that those with more than 5 years of work experience were at a greater risk of low back pain compared to less experienced workers. BMI is another characteristic that has been reported as an important risk factor for firefighter injury, meaning the higher one's BMI the greater risk of injury (Jahnke et al., 2013; Neitzel et al., 2016) and injury near misses among firefighters (Neitzel et al., 2015).

Given the highly physical nature of their work, it is not surprising that improved physical fitness has a positive correlation with firefighting ability test scores (e.g. Michaelides et al., 2008; Williford et al., 2010). Several researchers have recently hypothesized that targeted fitness training may help mediate the development of musculoskeletal disorders (MSDs) in firefighters (Beach et al., 2014; Frost et al., 2015), including low-back pain (Katsavouni et al., 2014). However, their research indicates that while exercise may have health benefits, it does not appear to have benefits on improving work-related postures that are associated with MSDs (Beach et al., 2014). Rather, efforts directed at improving work-related postures and movement strategies are suggested as more appropriate means to reduce work-related MSDs, in particular low back pain (Beach et al., 2014; Katsavouni et al., 2014). Before injury-reduction ergonomic training modules can be developed, a better understanding of posture strategies specific to fire suppression tasks used by firefighters is needed.

Fire suppression tasks often involve manual materials handling (MMH) tasks, such as pushing, pulling, and lifting of heavy or awkward loads. Oftentimes loads need to be picked up off the ground and carried or dragged some distance in a timely manner. Firefighters have the additional burden of wearing approximately 23.2 kg of heavy personal protective equipment, which includes bunker gear (boots, pants, jacket, helmet, and gloves) and a self-contained breathing apparatus (SCBA). In fact, the consistent use of an SCBA has been shown to increase risk of falls in firefighters (Heineman et al., 1989). Thus, the combination of loads, both borne and hand-held, and task constraints can cause firefighters to adopt a variety of postures that need to be better understood from an injury prevention perspective.

A frequently used method to survey the postures and movement strategies used in occupational environments is video observation. Video observation has been shown to be a valid ergonomic tool (e.g. Coenen et al., 2013), and is often preferred in field-based assessments over other exposure measurement tools, including self-report and direct measurement (e.g. electrogoniometry or electromyography). Self-report measurements, while efficient to use, can result in exposure over-reporting (Spielholz et al., 2001) and are generally less reliable than other exposure measurement tools (Balogh et al., 2004; Hansson et al., 2001). Although direct measurement has the potential to yield the most accurate data, it is often not feasible to use due to issues including tool portability, environmental challenges and participant clothing constraints. In contrast, video observation is often easily conducted in the field and can offer detailed data that can be reviewed and analyzed off-line (Spielholz et al., 2001) using tools such as the Rapid Upper Limb Assessment (RULA) (McAtamney & Corlett, 1993), the Rapid Entire Body Assessment (REBA) (Hignett & McAtamney, 2000) and the Ovako Working Posture Analysing System (OWAS) (Karhu et al., 1977). Each of these commonly used ergonomic tools (Kee & Karwowski, 2007) has a body segment posture scoring system that yields a cumulative action classification (AC) score associated with the urgency with which ergonomic attention is required for that specific task in order to reduce injury risk. RULA focuses on the upper extremity, neck, and trunk and has considerations for hand load magnitude and repetition, which makes it most suitable for sedentary and seated task assessments. REBA uses a similar approach to RULA but has additional inputs for knee flexion and hand coupling with the load. Although OWAS does not have hand coupling with the load, has fewer classification options for the upper extremity and no classifications for neck posture, OWAS has more specific categories for the lower extremity. This feature, paired with its classification of arm and trunk postures, and load magnitude makes OWAS an effective tool for occupations that require irregular (i.e. non-repetitive) full body physical exertions with high postural variation, such as construction work (Mattila et al., 1993), carpentry (Kivi & Mattila, 1991), and nursing (Engels et al., 1994). Furthermore, the focus of OWAS on arm, trunk, and leg postures is ideal for analysing firefighting tasks given that these are the three body regions where injuries are most common in this population (Frost et al., 2016; Kajaks & MacDermid, 2015).

The purpose of this study was to describe and evaluate the posture strategies used by firefighters as they perform three common and problematic fire suppression tasks: hose drag, hose pull, and high-rise pack lift and carry. Specifically, we wanted to better understand the types of postures used by firefighters during fire suppression tasks and if these postures place the firefighters at risk of sustaining a musculoskeletal injury. We also sought to determine if firefighter anthropometric and demographic characteristics were associated with increased risk of musculoskeletal injury due to posture selection during the fire suppression tasks. We hypothesized that the high-rise pack lift and carry task would result in the greatest injury risk because of the location and initial magnitude of the load as well as the tendency for firefighters to carry the pack over their shoulder. Both anthropometric and demographic variables were expected to contribute to the postures selected, and therefore to the overall urgency for ergonomic intervention for each task phase based on the OWAS AC score. Ultimately, the results of this study are expected to inform the priority with which each task is assessed for ergonomic intervention and, more generally, to inform the development of educational ergonomic training programs for firefighters.

2. Methods

2.1 Protocol Overview

Through a partnership with the Hamilton Firefighter's Association (FIRE-WELL), a cohort of 48 firefighters were recruited to perform three common hose-related firefighting tasks (hose drag, hose pull, and high-rise pack lift and carry) in full bunker gear, including jacket, pants, boots, gloves, helmet and self-contained breathing apparatus (SCBA) for a total weight of approximately 23.2 kg, at the Hamilton Firefighter Training Centre. Video observation was used to classify the postures during the initial hose pick-up (Task 1-3), hose manipulation (Task 1-3), and ambulation with the hose (Task 1 & 3).

2.2 Participants

Active firefighters (n = 48) were recruited internally through the Hamilton Firefighter's Association using email and word-of-mouth advertisements. All firefighters who were labelled 'fit-for-duty' were included in the study. At the time of data collection, firefighters were on-duty, and were therefore compensated for their time. (Note: unless explicitly discussing rank, the term "firefighters" will be used to refer to all participants in the present study.) Firefighters arrived at the training facility in groups of 7-12 people, which enabled adequate station coverage during the testing period. All firefighters provided written, informed consent, which was approved by the Hamilton Integrated Research Ethics Board. Prior to performing the firefighting tasks, demographic (age, tenure, and rank) and anthropometric data (height and weight) were recorded.

2.3 Experimental Set-up

Firefighters were required to wear full bunker gear, which included their issued custom-sized jacket, pants, boots, gloves, and helmet (10.3 kg ± 0.80 kg depending on the size of the equipment), as well as a self-contained breathing apparatus (SCBA) and mask (12.3 kg) (Figure 1).

All tasks were performed in a standardized format, using set start positions and equipment. Participants were asked to start each task by standing within a 0.3 m x 0.4 m box marked by tape on the floor of the Hamilton Firefighter Training Centre (Figure 1). Depending on the task, either a hose nozzle (6.1 kg) attached to a single length of 38 mm fire hose (length = 15.24 m, 4.19 kg) or a high-rise pack (19.5 kg, containing 2 fire hose lengths, a hose nozzle, and a tool kit) were centred over-top of a marker to the right of the starting box, at a distance of 0.3 m from the side of the box and in-line with the front of the box.

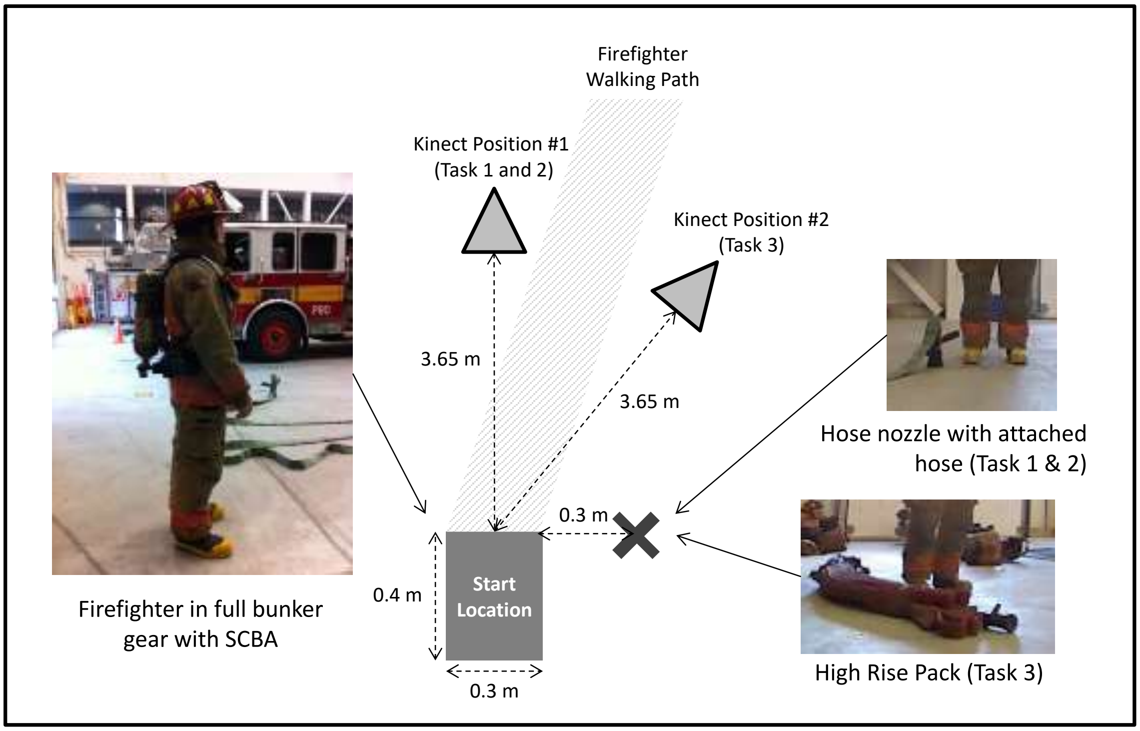


Figure 1: Diagram of experimental set-up demonstrating positions of the equipment and participant locations (not to scale).

A Microsoft Kinect® camera (Kinect for Xbox, Microsoft, WA, USA) was positioned at a height of 0.5 m and a distance of 3.65 m from the starting position, at a location that would maximize the frontal plane view of the firefighters as they performed the tasks (Figure 1). The 2D video data stream was saved during each collection session, with additional 3D depth data being collected to supplement the 2D data as a secondary data source. For the hose drag (Task 1) and hose pull (Task 2) tasks, the camera was located directly in front of the participants as they stood in their starting position. For the high-rise pack lift task (Task 3), where the more body rotation was typically used to pick up the pack, the camera was rotated by 35 degrees so that both the start posture and the pick-up posture could be adequately captured. Each firefighter performed each task once. Given that all firefighters were familiar with each of the tasks, all tasks were performed in the same order without randomization as there was no risk of a learning effect given the regularity with which the tasks are performed in the same training environment.

2.4 Tasks

The hose drag, hose pull, and high-rise pack tasks (Figure 2) were selected based on discussions with representatives from the Hamilton Firefighters Association who identified the tasks as common and challenging for firefighters. Additionally, these tasks are part of the Candidate Physical Ability Test (CPAT) (Deakin et al., 1996), but were modified for the present study by reducing the space in which these movements were performed so they could be captured using video. Unlike with the CPAT exam, firefighters were asked to perform the tasks as they would at a standard fire call, rather than as quickly as possible. These instructions were given due to the study's focus on posture assessment rather than performance as measured by time to task completion.

Figure 2: Sample images of the a) hose drag, b) hose pull, and c) high-rise pack lift and carry tasks.

2.4.1 Hose drag task

The hose drag task (Task 1) required that firefighters pick up a hose nozzle that was positioned standing on end at a standardized location, approximately 0.3 m from the front of the starting location to the immediate right of the firefighters (Figure 2). The hose was loosely coiled next to the nozzle. Once the nozzle was picked up, firefighters were then asked to take five steps forward while holding the hose nozzle and dragging the hose. Similar to the standard firefighting protocol, the hose was left uncharged for this task.

2.4.2 Hose pull task

For the hose pull task (Task 2), the hose nozzle was positioned standing on end in the standardized location, similar to the hose drag task, with the hose uncoiled in front of the start location. Firefighters were asked to pick-up the nozzle and/or hose and draw the hose towards them using a hand-over-hand approach until five movements per hand had been performed. As per standard protocol for this task, the hose was left uncharged.

2.4.3 High-rise pack lift and carry

The high-rise pack lift and carry task (Task 3) required that the high-rise pack be centred over the standardized starting position such that the length of the pack was parallel to the sagittal plane of the firefighter when in their starting position. Firefighters were asked to pick-up the pack, place it on their shoulder, and take five steps in the forward direction.

2.5 Video Data Collection and OWAS Analysis

Video data was collected using the Microsoft Kinect® System (Kinect V1, Microsoft Corps., WA, USA). The Microsoft Kinect® system collects both 2D video data using an RGB camera (640 x 480 Pixel resolution) as well as 3D depth data using an infrared emitter and receiver (320 x 480 pixel resolution). The system is designed to capture data at a maximum of 30 Hz.

Video observation was used to classify the posture strategies at different phases of each task using the OWAS ergonomics tool (Karhu et al., 1977). OWAS is a full-body observational posture assessment tool with intra-rater reliability of 95% by Kee & Karwowski (2007) and inter-rater reliability scores of 90% by Heinsalmi (1986) and 93% by Karhu et al. (1977). A researcher with experience using video observation for ergonomic analysis performed the posture classification using the 2D video data from the

Microsoft Kinect® system. Where necessary, the 3D depth data was used to supplement the 2D data in order to most appropriately classify the posture strategies. The OWAS tool evaluates single static postures. Therefore, the video data were scanned and a single representative frame from each critical phase of each task was selected. The following phases for each of the three tasks were evaluated using the OWAS tool:

- Task 1 (Hose drag): hose initial contact (Phase 1), ambulation preparation (Phase 2), and ambulation with hose (Phase 3)
- Task 2 (Hose pull): hose initial contact (Phase 1), and hose pull (Phase 2)
- Task 3 (High-rise pack lift and carry): hose initial contact (Phase 1), hose lift to shoulder (Phase 2), and ambulation with hose (Phase 3)

The OWAS tool uses seven lower extremity posture categories, four trunk posture categories, three shoulder posture categories, and three load categories to determine where the overall observed postures falls within one of four action classification (AC) scores for postural intervention (1: No action needed, 2: action needed in the near future, 3: action needed as quickly as possible, 4: immediate action required). (See Appendix A for the OWAS tool scoring system.)

2.6 Data Analysis:

SPSS software (IBM SPSS Statistics version 20, IBM, NY, USA) was used to conduct all statistical analyses.

Descriptive statistics were calculated for all demographic (age, sex, rank, and tenure), anthropometric (height, weight, and body mass index (BMI)), and OWAS ergonomic evaluation tool components.

The Wilcoxon Signed Ranks Test was used to test for differences in OWAS AC scores between each of the sub-tasks in order to determine which tasks required more urgent attention. A Bonferroni correction was applied to alpha due to the 28 comparisons (α = 0.05/28 = 0.0018). This non-parametric test was selected given the ordinal and paired nature of the variables being compared.

Chi-squared analyses were used to determine if there were significant associations between each of the demographic and anthropometric variables and the OWAS AC scores. To reduce the frequency of having insufficiently populated analysis tables, the median value for each of the continuous variables was used to categorize the variables into two groups (i.e. low/high). The OWAS AC scores were divided into two groups: low priority (AC scores 1 and 2), and high priority (AC scores 3 and 4). Job rank reports were also divided into two groups: firefighters and captains (i.e. captains and acting captains). Significance was determined using the Likelihood Ratio Chi-squared statistic given the small sample size with alpha corrected for the seven comparisons made for each task phase (α = 0.05/7 = 0.0071). The two-sided Fisher's Exact Test was used when there was a failure to achieve five items per category in 20 % of the categories.

3. Results

Overall, 48 firefighters were recruited and completed this study (Table 1). Six of these firefighters were female. Seven of the firefighters recruited were Captains while three were Acting-Captains, and all of these participants were male. The average age of the cohort was 43.0 years, with an average tenure of 14.8 years.

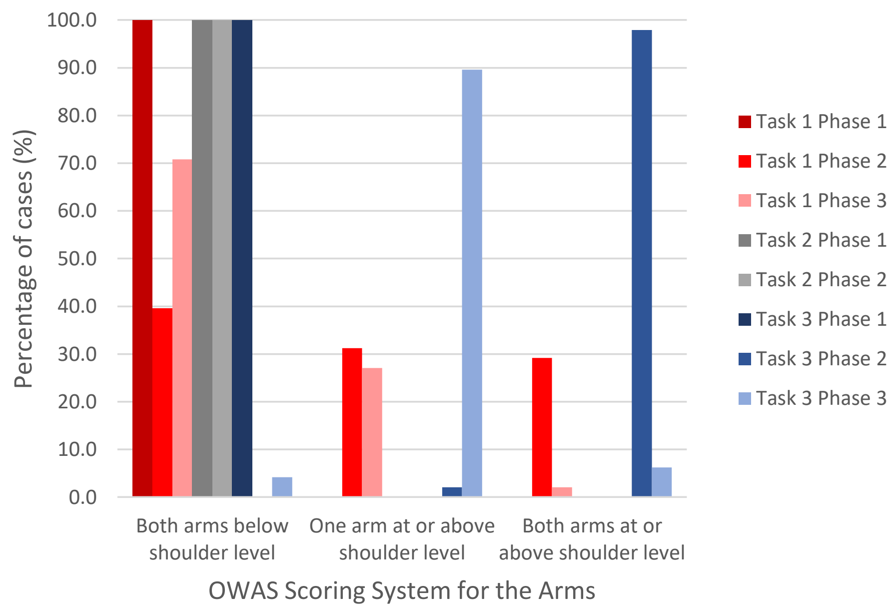
Table 1: Descriptive statistics for the independent variables collected from the participants.

		Age		Tenure		Height		Weight		BMI		Rank		
	N	**Mean (STD)**	**Median**	**Mean (STD)**	**Median**	**Mean (STD)**	**Median**	**Mean (STD)**	**Median**	**Mean (STD)**	**Median**	**Fire-Fighter**	**Acting-Captain**	**Captain**
Male	42	43.95 (8.82)	46.50	15.86 (8.70)	19.00	179.78 (8.94)	180.34	96.51 (11.08)	95.16	30.03 (4.33)	29.37	32	3	7
Female	6	36.00 (5.44)	35.00	7.00 (3.62)	5.50	167.68 (4.31)	168.91	69.99 (12.58)	65.45	24.82 (3.83)	23.28	6	0	0
Full Cohort	**48**	42.96 (8.84)	46.00	14.75 (8.73)	16.00	178.27 (9.38)	179.07	93.20 (14.23)	95.16	29.38 (4.57)	28.75	38	3	7

3.1 Description and Ergonomic Evaluation of Task Posture Selection

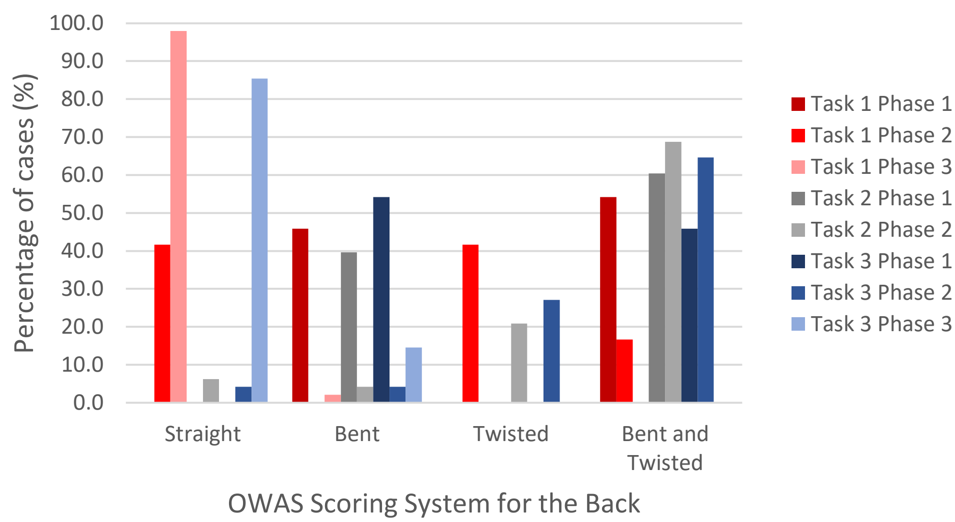
The individual scoring components of the OWAS tool are shown in Figure 3 to demonstrate the variability of observed postures. The overall mode of these OWAS results for each task phase is described in Table 2. Most firefighters chose to work with both arms below their shoulder height, although having one or both arms at or above shoulder height was most common during Phase 2 and Phase 3 of Task 3. A bent and twisted trunk posture was used by many firefighters in at least one of the task phases. Having a straight back was the most common posture for the ambulation phases (Phase 3) of Task 1 and Task 3. The two most commonly selected leg postures during the initial hose contact phases for each task were standing or squatting on two bent legs, and kneeling. Standing on two straight legs and walking were also frequently observed in Phases 2 and 3, respectively, of Task 1 and Task 3. The hand loads in this study were consistent for all firefighters within tasks because the same equipment was used for all firefighters. Thus, Task 1 and Task 2 required lifting a load under 10 kg while Task 3 required lifting a load above 10 kg and equal to or less than 20 kg.

The descriptive results from the OWAS assessment, as determined by the AC score, show that the initial contact phase of each task was the most problematic (Figure 3 and Table 2). The most reported (i.e. mode) AC score for this phase for each task was 4 (45.8 %, 54.2 %, and 45.8 % of the cases for Task 1, Task 2, and Task 3, respectively), indicating that immediate action is needed to correct issues with the task in order to prevent injury. The high-rise pack lift-to-shoulder phase was identified as warranting action as quickly as possible (56.3 % of cases), and the hose pull phase of Task 2 was identified as requiring improvements in the future (39.6 % of cases). The remainder of the phases identified that, in most cases, no action was required.



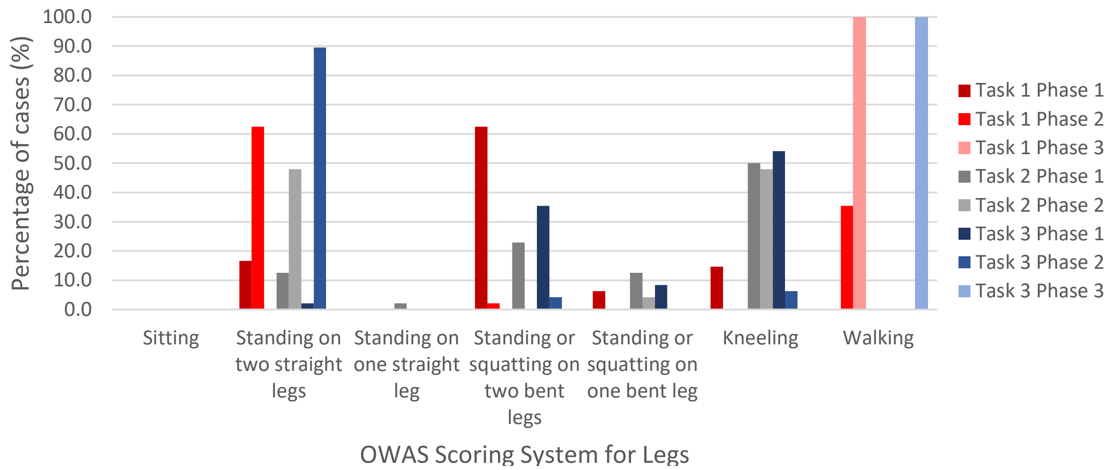
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
Percentage of cases (%)
Both arms below shoulder level
One arm at or above shoulder level
Both arms at or above shoulder level
OWAS Scoring System for the Arms
Task 1 Phase 1
Task 1 Phase 2
Task 1 Phase 3
Task 2 Phase 1
Task 2 Phase 2
Task 3 Phase 1
Task 3 Phase 2
Task 3 Phase 3

a)

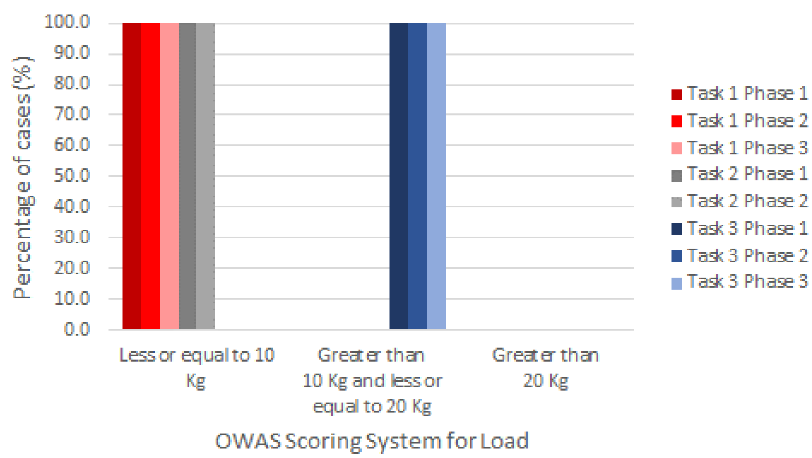


100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
Percentage of cases (%)
Straight
Bent
Twisted
Bent and Twisted
OWAS Scoring System for the Back
Task 1 Phase 1
Task 1 Phase 2
Task 1 Phase 3
Task 2 Phase 1
Task 2 Phase 2
Task 3 Phase 1
Task 3 Phase 2
Task 3 Phase 3

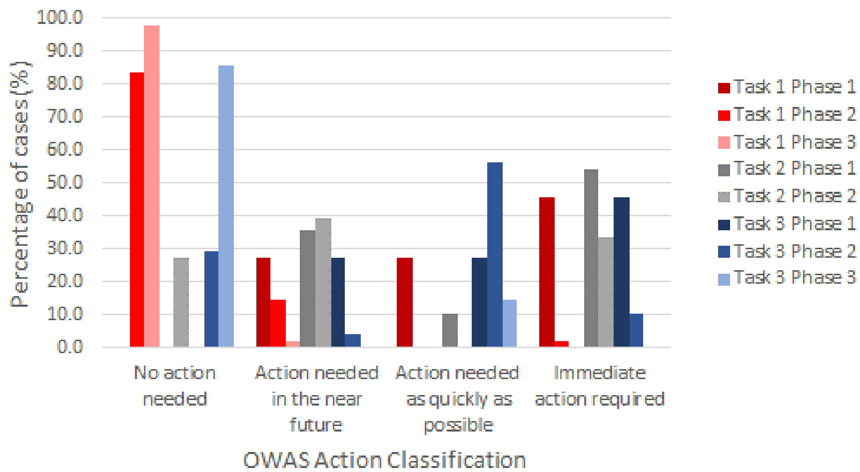
b)


100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
Percentage of cases (%)
Sitting
Standing on two straight legs
Standing on one straight leg
Standing or squatting on two bent legs
Standing or squatting on one bent leg
Kneeling
Walking
OWAS Scoring System for Legs
Task 1 Phase 1
Task 1 Phase 2
Task 1 Phase 3
Task 2 Phase 1
Task 2 Phase 2
Task 3 Phase 1
Task 3 Phase 2
Task 3 Phase 3

c)


100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
Percentage of cases (%)
Less or equal to 10 Kg
Greater than 10 Kg and less or equal to 20 Kg
Greater than 20 Kg
OWAS Scoring System for Load
Task 1 Phase 1
Task 1 Phase 2
Task 1 Phase 3
Task 2 Phase 1
Task 2 Phase 2
Task 3 Phase 1
Task 3 Phase 2
Task 3 Phase 3

d)



e)

Figure 3: Percent of total cases (n = 48) for each scoring component of the OWAS tool across all 48 firefighters including the: a) arms, b) back, c) legs, and d) load for each of the task phases. The OWAS AC score (e) is also displayed for each task phase as a percentage of total cases.

Table 2: Mode of the results and frequency of occurrence (%) for each item scored on the OWAS tool.

	Task 1			Task 2		Task 3		
	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 1	Phase 2	Phase 3
OWAS Item	Hose initial contact	Ambulation preparation	Ambulaton with hose	Hose initial contact	Hose pull	Hose initial contact	Hose lift to shoulder	Ambulaton with hose
Arms	Both arms below shoulder level 100%	Both arms below shoulder level 40%	Both arms below shoulder level 71%	Both arms below shoulder level 100%	Both arms below shoulder level 100%	Both arms below shoulder level 100%	Both arms at or above shoulder level 98%	One arm at or above shoulder level 90%
Back	Bent and Twisted 54%	Straight 42%	Straight 98%	Bent and Twisted 60%	Bent and Twisted 69%	Bent 54%	Bent and Twisted 65%	Straight 85%
Legs	Standing or squatting on two bent legs 63%	Standing on two straight legs 63%	Walking 100%	Kneeling 50%	Kneeling 48%	Kneeling 54%	Standing on two straight legs 90%	Walking 100%
Load	≤ 10 kg 100%	≤ 10 kg 100%	≤ 10 kg 100%	≤ 10 kg 100%	≤ 10 kg 100%	10 kg < x ≤ 20 kg 100%	10 kg < x ≤ 20 kg 100%	10 kg < x ≤ 20 kg 100%
AC Score	Immediate action required 46%	No action needed 83%	No action needed 98%	Immediate action required 54%	Action needed in the near future 40%	Immediate action required 46%	Action needed as quickly as possible 56%	No action needed 85%

The Wilcoxon Signed Ranks Test was used to identify the priority order in addressing the ergonomic issues between task phases based on their OWAS AC scores (Table 3). The task phases requiring the most urgent attention were the initial hose contact phases of each task. While no significant differences were found between each of these phases, Task 2 had a median AC score of 4 and Task 1 and Task 3 had median AC scores of 3 in the initial hose contact phase. Thus, by virtue of the meaning of an OWAS score of 4, Task 2 Phase 1 requires immediate action whereas the other two task phases require action "as quickly as possible" but are not as urgent as Task 2 Phase 1. Task 3 Phase 2, or the phase where the high-rise pack was lifted to the shoulder, also requires action "as quickly as possible". There is no statistical difference between Task 3 Phase 2 and Task 3

Phase 1 (p = 0.005), or the initial hose contact with the high-rise pack. However, Task 3 Phase 2 ranks as a lesser priority compared to Phase 1 of the other two tasks (Task 1 Phase 1: p = 0.002; Task 2 Phase 1: p = 0.002). The only other task phase that needs to be addressed from an injury prevention perspective (i.e. has an OWAS AC score above 1) is Task 2 Phase 2, or the hose pull phase, which was identified as requiring action "in the near future". Although this task is not statistically different from Task 3 Phase 2 (p-value = 0.580), it has a median OWAS AC score of 2 compared to an OWAS AC score of 3 for Task 3 Phase 2. Task 1 Phase 2 (ambulation preparation) and 3 (ambulation) and Task 3 Phase 2 (ambulation), each of which has an OWAS AC score of 1 indicating no action needed, are not different from each other, but are significantly smaller than the other Task Phases.

3.2 Associations between Ergonomic Evaluations and Firefighter Characteristics

Associations between OWAS AC scores and independent variables, including demographic and anthropometric variables, were examined using a chi-squared analysis (Table 4). The only significant association was BMI with the Task 3 Phase 1 OWAS AC score, where a BMI less than 28.75 was associated with a high AC score (Likelihood ratio: 9.20, p-value = 0.002). No other significant associations were identified. The Chi-squared analysis could not be run for Task 1 Phase 3 because all of the OWAS AC scores fell into the "low AC score" creating an incomplete matrix for the analysis.

Table 3: Wilcoxon Signed Ranks Test results for each pair of task phase comparisons of OWAS AC scores. The median OWAS scores for each pair of Task Phases are on the upper right of the table, with the p-value of the comparison directly below these scores. For the median scores, the top value corresponds to the task phase in the respective column and bottom value corresponds to the task phase in the respective row. Cells that are in bold demonstrate significant differences between compared task phase OWAS AC scores. Where significant differences lie, the associated task phase OWAS AC median scores provide insight into the ranked order of the pair. The bottom row contains the ranking of ergonomic prioritization (highest to lowest) based on the 28 comparisons of the Wilcoxon Signed Ranks Test.

		Median OWAS Action Classification Scores (Top: row, Bottom: column)							
		Task 1 Hose Pull			**Task 2** Hose Drag		**Task 3** High-rise Pack Lift		
		Phase 1	**Phase 2**	**Phase 3**	**Phase 1**	**Phase 2**	**Phase 1**	**Phase 2**	**Phase 3**
Task 1 Hose Pull	**Phase 1**		**1** **3** **0.0000**	**1** **3** **0.0000**	4 3 0.9505	**2** **3** **0.0001**	3 3 0.9232	**3** **3** **0.0018**	**1** **3** **0.0000**
	Phase 2			1 1 0.0209	**4** **1** **0.0000**	**2** **1** **0.0000**	**3** **1** **0.0000**	**3** **1** **0.0000**	1 1 0.3231
	Phase 3				**4** **1** **0.0000**	**2** **1** **0.0000**	**3** **1** **0.0000**	**3** **1** **0.0000**	1 1 0.0104
Task 2 Hose Drag	**Phase 1**					2 4 0.0023	3 4 0.8319	**3** **4** **0.0020**	**1** **4** **0.0000**
	Phase 2						**3** **2** **0.0006**	3 2 0.5799	**1** **2** **0.0000**
Task 3 High-rise Pack Lift	**Phase 1**							3 3 0.0048	**1** **3** **0.0000**
	Phase 2								**1** **3** **0.0000**
	Phase 3								
OWAS Action Priority Rank (highest (1) to lowest (2))		1	4	4	1	3	1	2	4

Table 4: Chi-squared analysis for the OWAS AC scores for each task phase compared with each of the demographic and anthropometric variables.

OWAS AC Scores	Sex	Age	Weight	Height	BMI	Tenure	Rank
	Ref: male	Ref: young age	Ref: low weight	Ref: short height	Ref: low BMI	Ref: Junior	Ref: Firefighter
(Ref: low AC)	Likelihood ratio	Likelihood ratio	Likelihood ratio	Likelihood ratio	Likelihood ratio	Likelihood ratio	Likelihood ratio
Task 1 Phase 1	4.10	1.24	0.01	0.11	2.69	2.15	0.34
Task 1 Phase 2	0.27	2.12	0.95	1.41	1.41	1.49	0.47
Task 1 Phase 3	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Task 2 Phase 1	1.17	0.00	0.75	0.82	4.56	0.01	1.41
Task 2 Phase 2	0.82	0.18	0.41	1.51	0.00	0.17	0.06
Task 3 Phase 1	4.10	3.43	0.35	2.69	9.20*	2.15	2.17
Task 3 Phase 2	0.00	0.72	0.00	0.38	0.00	2.06	0.06
Task 3 Phase 3	0.02	0.17	2.13	0.17	0.17	1.27	0.28

Note: Age. anthropometric, and tenure variables were divided in to two groups based on the median value of each variable. Two groups were formed for Rank: those who were firefighters, and those who had other titles (e.g. captain, acting-captain, etc.). AC scores were also divided into two groups, with AC scores of 1 and 2 in the low priority group and 3 and 4 in the high priority group.

4. Discussion

3.1 Description and Ergonomic Evaluation of Task Posture Selection

The evaluation of three common simulated fire suppression tasks has identified that task phases where the hose is lifted either up off the ground or to shoulder height, rather than simple movement or ambulation with the hose, are those most in need of ergonomic attention to reduce or prevent injury to firefighters. Overall, Task 3, the high-rise pack lift and carry task, was identified as being in the most urgent need of ergonomic action based on having two of three phases (initial hose contact and hose lift-to-shoulder) identified as in need of action "as quickly as possible" for most firefighters. These findings are in-line with recent research by Frost et al. (2016) that identified bending, lifting and/or squatting as the general motion pattern most frequently performed at the time of work-related musculoskeletal injuries in firefighters. Indeed, in order to lift a hose up off the ground, as is needed in the initial phase of each task performed in the current study, either bending or squatting combined with a lifting movement is required. Gentzler and Stader (2010) used observational methods and ergonomic tools (NIOSH lifting equation, RULA, and REBA) to study post-fire tasks (hose lift to drain and hose rolling). Their posture-related injury risk findings highlight similar trends to those found in the current study, where lifting above the shoulder and working with hoses at ground-level were reported as being at high to very high injury risk levels.

A closer examination of the sub-components of the OWAS tool allows for a better understanding of why these task phases have been flagged as in need of ergonomic action. Common features across these problematic task phases included the use of bent and twisted back postures and leg postures involving kneeling, squatting, and standing with two bent legs. Again, these findings highlighting the role played by the postures of the back and leg in the high OWAS ergonomic action scores are supported by the general movement patterns used by Calgary firefighters at the time of injury (Frost et al., 2016).

In Task 3, additional factors contributing to the need for ergonomic action included working with one or both arms at or above shoulder height and the greater load of the high-rise pack. Interestingly, Frost et al. (2016) reported that all of the shoulder injuries to firefighters at the Calgary Fire Department in 2012 occurred during non-fire-related activities, such as training at the firefighter training center, performing physical training, fulfilling duties at the fire station, or attending to non-fire-related emergency calls. Since the tasks evaluated in this study were simulated fire suppression tasks performed within the context of the training center, we can infer, based on the report by Frost et al. (2016), that the observed postures were performed with no less injury potential than they would at a real fire and are therefore good examples of the postures that may lead to injury in this workforce. However, to be certain of this inference, a similar evaluation of the injury statistics conducted at the Calgary Fire Department is needed for the Hamilton Fire Department.

4.2 Associations between Ergonomic Evaluations and Firefighter Characteristics

Our findings show that, in general, firefighter anthropometric and demographic characteristics were not associated with the selection of postures by firefighters during the three simulated fire suppression tasks. The only exception to this observation was the association between BMI, which is a ratio of weight to height, and the final OWAS AC score for the initial host contact phase of Task 3, where a low BMI was associated with a high OWAS AC score or a more urgent need of ergonomic action. This association was in the opposite direction to that previously reported in the literature, where a higher BMI was associated with a greater risk of injury to firefighters (Jahnke et al. 2013; Neitzel et al., 2015). Given that neither height nor weight were associated with the final OWAS AC score, it is possible that increased muscle mass, and therefore strength, may explain the association between having a higher BMI and choosing less risky postures to perform the same task by our cohort of firefighters. Indeed, firefighters have been considered occupational athletes given the great physical demands required of them (Frost et al. 2015), which makes it reasonable to assume that an increased BMI in this population may be associated with greater muscle mass. However, the association found in our study between BMI and OWAS AC score was unique to a single task phase and was not observed elsewhere in the analysis. It is also important to note that while BMI is used as a measure of obesity, it is possible to have a high BMI as a result of significant lean body mass relative to height, which would result in a potentially more fit, stronger, and safer firefighter. Indeed, a lower percent body fat has been associated with greater firefighter fitness (Poplin et al., 2016) and better performance on the Firefighter's Ability Test (Michaelides et al., 2008).

Age, and the associated variable of tenure, were hypothesized to be associated with final OWAS AC scores, although the direction of the relationship was uncertain. We considered that increased age might translate into more experience along with the opportunity to learn or hone in on safer postures, which would contribute to a decrease in OWAS AC scores. Alternatively, we also expected that junior firefighters would be more likely to adopt safer postures based on their recent familiarity with health and safety training taken as new recruit. Although no association between age and injury risk was found in the current study, the literature has evidence of a relationship between these two variables, particularly with respect to low back pain (Katsavouni et al., 2014; Lett & McGill, 2006). However, the literature demonstrates conflicting associations. Lett and McGill (2006) showed that more experience in four professional firefighters compared to five novice males contributes to improved technique, which translates into decreased shear and compression forces during pushing and pulling tasks as determined by advanced biomechanical modeling. Katsavoumi et al. (2013) used an epidemiological approach with 3451 firefighters (124 female) to determine that those who had been working more than five years had a greater risk of low back pain (OR: 2.39, CI: 1.92-2.96). More work is needed to understand what, if any, modifiable risk factors (e.g. recent ergonomic training or exercise regime) contribute to these associations between age and risk of low back pain.

Sex and job category were also expected to be associated with OWAS AC scores, but this relationship was not found in the current study. The literature, however, does show that female firefighters are at a greater risk of low back pain than their male counterparts, and firefighter officers have a decreased risk of low back pain compared to fire truck drivers (Katsavouni et al., 2014). This highlights the fact that different people within fire service may perform different job tasks, and the risk is associated with the tasks not the job category. In drawing conclusions from our study, it is important to note that while the OWAS AC scores are used as a surrogate for injury risk, there are other risk factors that likely play a role in injury risk above and beyond the pure postures and hand loads assessed by the OWAS tool. These factors may be task-related, such as handle height for pushing and pulling (e.g. Lett and McGill, 2006), fitness-related, such as flexibility (e.g. Neitzel et al., 2016; Poplin et al., 2015) or psychosocial such as perceived job demands (Neitzel et al., 2015).

4.3 Study Limitations

Overall, the OWAS tool is well aligned with the ergonomic assessment needs of the firefighter population because it focuses on the back, arms, and legs, which are the three body regions that have been identified as most problematic in the firefighter population (Frost et al., 2016; U.S. Department of Homeland Security, 2011; WSIB, 2016), and in particular, within our cohort of firefighters (Kajaks & MacDermid, 2015). However, there are limitations to using this tool that need to be acknowledged.

Specifically, the OWAS tool uses minimal and general posture categories with broad bin definitions to evaluate the need for ergonomic action. While this allows for quick and simplified assessments, it positions the tool as more of a screening tool rather than a sophisticated quantitative ergonomic assessment tool such as the NIOSH lifting equation. However, analyses of other posture-matching software, such as 3D Match, have highlighted the potential for misclassification of postures due to bin boundaries, which can impact the overall ergonomic risk factor score (Andrews et al., 2008). As demonstrated by intra- and inter-rater reliability scores over 90% (Heinsalmi, 1986;

Karhu et al., 1981; Kee & Karwowski, 2007) misclassification of postures is less of a concern with the OWAS tool given the broad boundaries with the OWAS tool.

The simplicity of the OWAS tool is also evident given its inability to account for load exposure factors such as movement frequency, recovery, or duration, as described in a review of ergonomic methods by David (2005). However, given the unpredictable work demands of firefighters, these additional factors cannot be reliably determined or estimated over the course of a work shift. Thus, the simplicity of the OWAS tool is both appropriate and ideal as an initial ergonomic assessment of simulated firefighter tasks.

Additional limitations to the study methodology included that the posture evaluation was restricted to a single representative static posture for each task phase of interest, with the body-borne external loads were not accounted for in the analysis. The focus on static postures without accountability for external loads is not simply a limitation of the OWAS tool itself as the selected tool but rather a limitation of the current suite of ergonomic tools available. A more dynamic assessment of the movements made by the firefighters as they wore complete bunker gear and manually manipulated heavy loads would have allowed for potentially important inertial properties of the system to be accounted for. However, the vast majority of current ergonomic tools are not yet advanced enough to account for these loads. Furthermore, the degree to which the single trial evaluated is representative of the actual postures used by the firefighters in both training and real fire suppression tasks is questionable. We made an *a priori* assumption that the simplicity and firefighter familiarity with the tasks warranted keeping the design simple enough to ask firefighters to only perform the task in question one time. Future work should evaluate the reproducibility of the observed firefighter postures in real training or active fire suppression environments.

Lastly, a sample of 48 firefighters (n = 6 female) volunteered to participate from a cohort of 471 total full-time firefighters (n = 13 female). This sample provided sufficient power to examine the breadth of postures used during the three selected simulated fire suppression tasks. However, the sample was small for the more sophisticated statistical analyses that may have otherwise allowed for associations between firefighter characteristics and OWAS AC scores to be determined.

4.4 Implications on Ergonomic Training Programs for Firefighters

The over-arching motivation for conducting this study was to gather information that can inform existing ergonomic training programs for firefighters. Previous research related to injury prevention of firefighters has largely focused on identifying demographic, anthropometric, and health-related risk factors (e.g. Jahnke et al. 2013; Michaelides et al. 2008; Neitzel et al. 2015; Poplin et al., 2016). Few studies, however, have used the more traditional ergonomic assessment approach and focused on movement and posture mechanics in this population. Those that have investigated the relationship between firefighter injury risk and movement mechanics have done so using tasks that are not directly work-related, such as generic pushing and pulling tasks (Lett and McGill, 2006) or fitness training programs (Beach et al. 2014; Frost et al., 2015). The relevance of these study findings to injury prevention during real or training-related fire suppression tasks has not been clearly demonstrated. In fact, Beach et al. (2014) found that while fitness measures improved as a result of a 12-week exercise program, these improvements were not observed in the Functional Movement Screen ™ Scores or occupational low back loading measures. As a result, a purely fitness-based intervention for injury prevention in firefighters was not recommended. However, Frost et al. (2015) did find improvements in outcomes that are more transferable to the work-related activities performed at fires (i.e. fireground activities), such as spine and knee motion control, in firefighters undergoing a 12-week movement-guided fitness program rather than a conventional fitness program. The approach shows promise as a behavioural learning method that engrains safer movement patterns into the regular duties of firefighters.

Thus, a movement-oriented approach to the training of high-injury risk tasks that is grounded in an understanding of safe and dangerous body mechanics during common firefighting tasks and taught directly within the context of firefighting, rather than during gymnasium-based training, is expected to be a successful way of teaching the behaviours that will ultimately lead to safer movement strategy selection by firefighters. The first step in developing this training program is to better understand which tasks place firefighters at risk of injury, and why. The current research has provided this information for three common fire suppression tasks. Next, we must work to develop a training program that incorporates what was learned from this study. For those tasks requiring ergonomic action, in-depth investigations using more sophisticated ergonomic tools and kinematic analyses (e.g. Sinden & MacDermid, 2016) is needed to determine how the tasks can be improved. Further research is also needed to better understand if and how postures differ between training environments and those used during emergency and non-emergency calls, as well as to ensure that the training programs do not need to be tailored based on firefighter characteristics (e.g. anthropometrics and demographics). Lastly, in addition to focusing on better training for firefighters, there should be parallel efforts looking at ways to redesign the tasks and equipment used to make the work environment as safe as possible for firefighters given their high risk of injury.

5. Conclusion

Firefighters are considered occupational athletes because of the high physical, cardiovascular, and cognitive demands placed on them to ensure the safety of the community. Unfortunately, this job too often leaves firefighters with work-related musculoskeletal injuries, among other health complications. Ensuring that firefighters have the ergonomic training to safely perform their tasks is an important factor in preventing these injuries. This current work provides insight into which phases of three common fire suppression tasks may place firefighters at risk of injury. This information is an important first step in gathering the information needed to develop effective training programs to help reduce the injury risks to firefighters.

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Appendix A: OWAS Tool Action Classification Scoring System

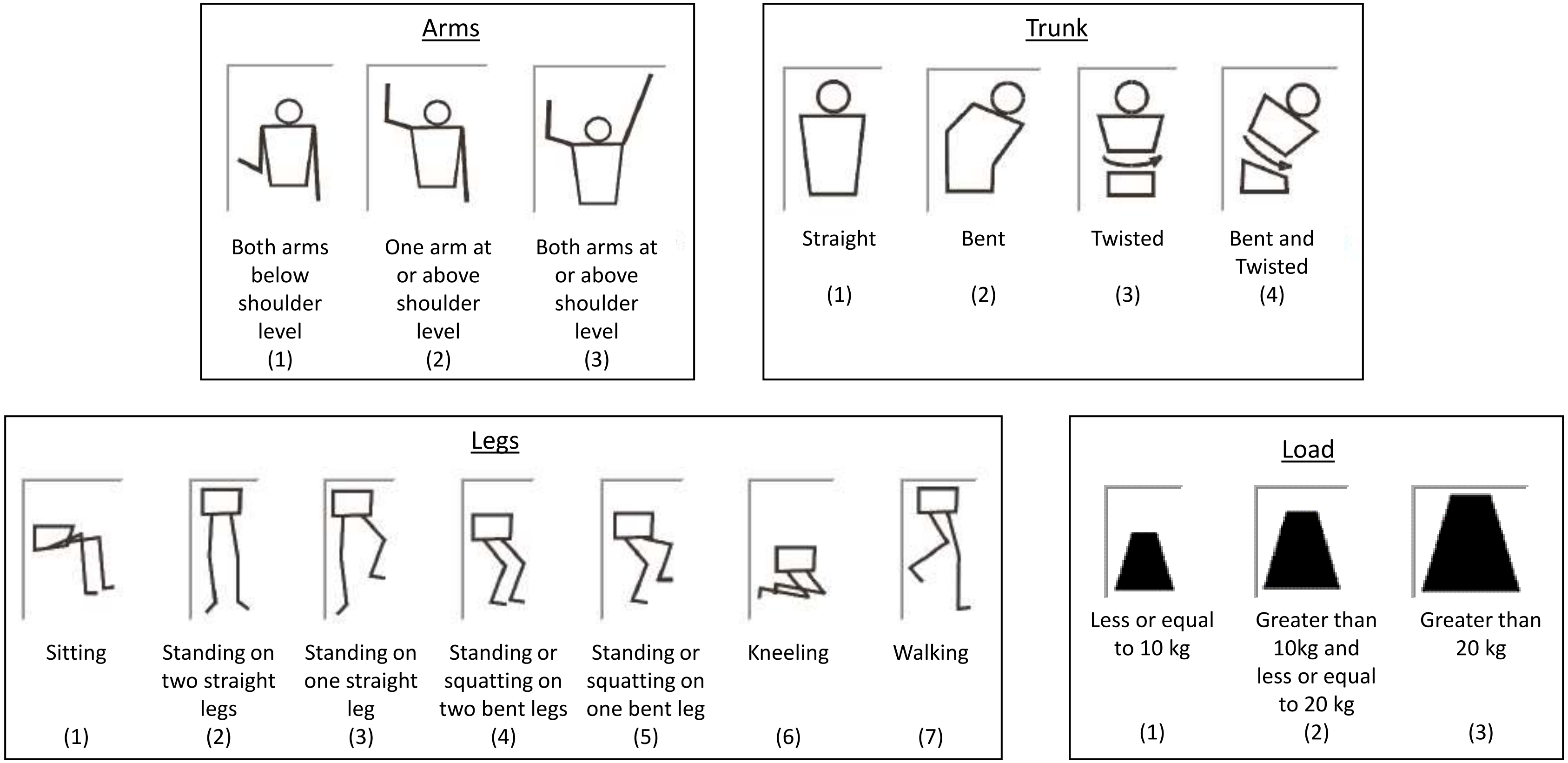
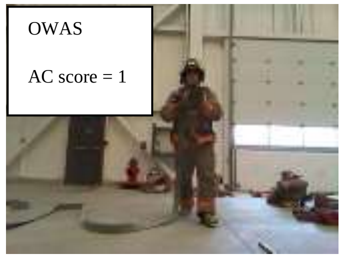


Figure A.1: OWAS ergonomic tool posture categories (Images adapted from the ErgoFellow 3.0 tool, http://www.fbfsistemas.com/imageserg.html).

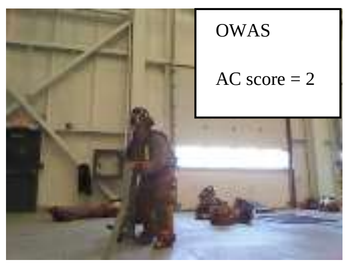
Table A.1: OWAS Tool Action Classification Scoring System based on OWAS Classifications (1: No action needed, 2: action needed in the near future, 3: action needed as quickly as possible, 4: immediate action required)

Back		Arms		Legs																				
				1			2			3			4			5			6			7		
				Sitting			Standing on two straight legs			Standing on one straight leg			Standing or squatting on two bent legs			Standing or squatting on one bent leg			Kneeling			Walking		
				Load			Load			Load			Load			Load			Load			Load		
				1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
				≤ 10 kg	> 10 kg, ≤ 20 kg	> 20 kg	≤ 10 kg	> 10 kg, ≤ 20 kg	> 20 kg	≤ 10 kg	> 10 kg, ≤ 20 kg	> 20 kg	≤ 10 kg	> 10 kg, ≤ 20 kg	> 20 kg	≤ 10 kg	> 10 kg, ≤ 20 kg	> 20 kg	≤ 10 kg	> 10 kg, ≤ 20 kg	> 20 kg	≤ 10 kg	> 10 kg, ≤ 20 kg	> 20 kg
1	Straight	1	Both Arms Below Shoulder Level	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	1	1	1	1	1	1
		2	One arm at or above shoulder level	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	1	1	1	1	1	1
		3	Bother arms at or above shoulder level	1	1	1	1	1	1	1	1	1	2	2	3	2	2	3	1	1	1	1	1	2
2	Bent	1	Both Arms Below Shoulder Level	2	2	3	2	2	3	2	2	3	3	3	3	3	3	3	2	2	2	2	3	3
		2	One arm at or above shoulder level	2	2	3	2	2	3	2	3	3	3	4	4	3	4	4	3	3	4	2	3	4
		3	Bother arms at or above shoulder level	3	3	4	2	2	3	3	3	3	3	4	4	4	4	4	4	4	4	2	3	4
3	Twisted	1	Both Arms Below Shoulder Level	1	1	1	1	1	1	1	1	2	3	3	3	4	4	4	1	1	1	1	1	1
		2	One arm at or above shoulder level	2	2	3	1	1	1	1	1	2	4	4	4	4	4	4	3	3	3	1	1	1
		3	Bother arms at or above shoulder level	2	2	3	1	1	1	2	3	3	4	4	4	4	4	4	4	4	4	1	1	1
4	Bent and Twisted	1	Both Arms Below Shoulder Level	2	3	3	2	2	3	2	2	3	4	4	4	4	4	4	4	4	4	2	3	4
		2	One arm at or above shoulder level	3	3	4	2	3	4	3	3	4	4	4	4	4	4	4	4	4	4	2	3	4
		3	Bother arms at or above shoulder level	4	4	4	2	3	4	3	3	4	4	4	4	4	4	4	4	4	4	2	3	4

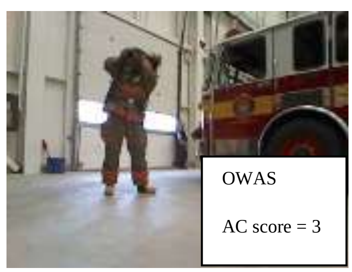
Appendix B: Sample Postures

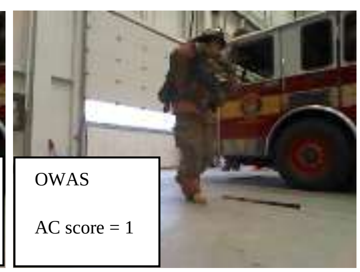


a) b) c)



d) e)





f) g) h)

Figure B: Sample postures and associated OWAS AC scores for the hose drag task (Task 1): a) hose initial contact (Phase 1), b) ambulation preparation (Phase 2), and c) ambulation with hose (Phase 3); the hose pull task (Task 2): d) hose initial contact (Phase 1), and e) hose pull (Phase 2); and the high-rise pack lift and carry (Task 3): f) hose initial contact (Phase 1), g) hose lift to shoulder (Phase 2), and h) ambulation with hose (Phase 3).

CHAPTER 4: ERGONOMIC ASSESSMENTS OF FIREFIGHTERS IN FULL BUNKER GEAR

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Abstract

The nature of a firefighter's work together with their personal protective equipment, present challenges in conducting ergonomic assessments. This research provides insight into the development of a firefighter ergonomic analysis protocol using digital human model (DHM) tools and Microsoft Kinect® video observation. Jack and 3DSSPP were used to assess twelve firefighters in full bunker gear performing the initial pick-up of a high-rise pack. Ergonomic risk was assessed using Static Strength Prediction (SSP), the NIOSH Action Limit (AL), and OWAS. Different posture acceptability (i.e. safe vs. unsafe) was observed (Cochrane's Q-test, $p<0.001$) due to the DHM software, the ergonomic tool, and the sophistication of the external load biomechanical modeling. The OWAS tool was the most conservative measure, followed by and assessment of L_4-L_5 compression forces using the NIOSH AL, and the SSP tool. The advantages, challenges, and opportunities for using DHM software in firefighter ergonomics are discussed based on these results.

Keywords: Firefighter, Microsoft Kinect®, posture analysis, OWAS, Static Strength Prediction, musculoskeletal injury prevention, biomechanical modeling, load carriage

1. Introduction

Firefighters are at high risk of musculoskeletal injury due, in part, to the nature of their work, their work environment when attending to a call, and the personal protective equipment (PPE) they wear during fire suppression tasks (Smith, 2011). These factors present challenges in using observational tools and direct measurement to conduct ergonomic assessments to better understand and reduce injury risks. For instance, objective evaluation of real fire suppression tasks, where many of the musculoskeletal injuries are reported to occur (Haynes & Molis, 2016), is difficult due to the extreme working conditions, immediacy of most tasks, unpredictable task assignment, PPE, and use of multiple tools. Furthermore, the safety of the firefighters, research team, and community-at-large must also be taken into consideration when assessing the ergonomics of field-based fire suppression tasks. However, re-creations of firefighter suppression tasks can be performed in firefighter training facilities that allow the optimal balance between realistic task simulation with the environmental controls characteristic of lab-based environments.

Although generally more favourable for in-depth biomechanical analyses, traditional laboratory-based methods typically have the burden of heavy participant instrumentation, such as electromyography and/or marker-based optimal motion capture (e.g. Lett & McGill, 2006) and cannot accommodate large equipment such as stairs or firetrucks. These methods can be a challenge in certain occupations, such as firefighting, where PPE and other equipment, which are critical to the task, can introduce significant measurement error. Furthermore, laboratory methodologies that use direct measurement can have the consequence of rendering natural movements more difficult or awkward as they can induce a “white coat effect” whereby participants feel uncomfortable performing in a naturalistic manner (Geh et al., 2011). Thus, efforts to collect data in field-based environments are, in theory, more preferred when the goal is applied research. A significant disadvantage to field-based data collection has always been the limited number of high quality tools available for valid and precise motion capture. The advent of field-friendly and minimalistic (i.e. not a heavy equipment burden) markerless motion capture tools, such as the Microsoft Kinect® system (Microsoft Corporation, Redmond, WA, USA), can enable sophisticated 3D data to be easily collected outside of the lab. These technological advancements are considered a substantial step forward in studying the physical demands of occupations like firefighting.

The Microsoft Kinect® system was originally developed as a gaming tool; however, the release of a Windows version in 2012 allowed for a broader application of the tool, particularly in the fields of rehabilitation sciences and ergonomics. The markerless 3D skeletal tracking capabilities of this single-unit portable device make it appealing for lab-based or clinical data (Bonnechere et al., 2014; Clark et al., 2013; Wang et al., 2015), as well as field-based applications (Colombo et al., 2013; Plantard et al., 2015). The literature highlights that, despite largely controlled studies describing small inaccuracies in the skeletal tracking capabilities of the Microsoft Kinect®, the tracking is sufficient for many novel applications including postural biofeedback (e.g. Clark et al., 2013) and as input into ergonomic tools (e.g. Plantard et al., 2015; Ray & Teizer, 2012).

The Microsoft Kinect® may be a viable, inexpensive and easy-to-use motion capture tool for field-based data collection. This tool may also simplify and accelerate the process of gathering and inputting data into ergonomic tools. Plantard et al. (2015) conducted a pilot study where they collected real upper limb movements from one participant using the Microsoft Kinect® and automatically classified the postures based on upper limb joint angles in accordance with the RULA ergonomic tool (McAtamney & Corlett, 1993). Despite the limited sample size, they collected over 500,000 data points and were able to conclude that the Microsoft Kinect® yielded joint angle results that were sufficient to complete the RULA evaluation. However, they also found that errors as high as 46 degrees in shoulder flexion were captured depending on the pose being evaluated and the positioning of the device. Ray and Teizer (2012) also used the Microsoft Kinect® to automatically classify observed postures into one of four categories: 1) standing, 2) squatting or sitting, 3) stooping or bending, and 4) crawling. Once classified, the postures underwent a customized ergonomic evaluation that included considerations for overhead work and lifting loads. Data from three participants was used to build the classifiers while data from five participants was used to validate the classifiers. An error rate for posture classification was 19.69 %, with the crawling posture being the most difficult to detect.

While these studies show promise for automated ergonomic tools using the Microsoft Kinect®, adopting a hybrid approach, whereby Microsoft Kinect® data can be visually inspected and manually corrected prior to sending the posture data for ergonomic analysis may be a more viable approach given the reported inaccuracies with the skeletal tracking capabilities of the Microsoft Kinect®. A potential ergonomic software package with which to do this is the Jack digital human model (DHM) tool (Siemens PLM, Plano, TX, USA). Jack allows users to either manually manipulate DHMs or drive their movements using motion capture data streams (Kajaks et al., 2011), including Microsoft Kinect® data, in order to create simulated virtual reconstructions of a task. A full suite of ergonomics tools can then be easily executed on the Jack DHMs, including the Ovako Working Posture Analysis System (OWAS), the Static Strength Prediction (SSP) tool, and the NIOSH Action Limit (AL). The OWAS tool uses a broad full-body assessment to determine if a posture is in need of ergonomic action (Karhu et al., 1977). The SSP tool determines if a task is acceptable based on whether or not 75% of the population has the full-body strength to perform the task (Don B. Chaffin & Erig, 1991). Finally, the NIOSH AL focuses exclusively on the low back, and labels a task safe if the workers' calculated L_4-L_5 compression forces are below 3400 N (NIOSH, 1981). This 3400 N threshold is the threshold whereby 75% of female workers and 99% of male workers can still safely perform the task.

Jack has been most widely used in the automotive manufacturing industry. Data collected through this software can assess injury risk factors of assembly line workers of both current workstations and of workstations being designed for future vehicle models in order to detect and modify tasks that may cause injury (Fiacco et al., 2009; Kajaks et al., 2011). An important feature of Jack is its ability to import computer-aided design (CAD) files into the virtual environment for interaction by the DHMs. Such interactions are particularly useful in fields like automotive manufacturing where the posture required to perform a task may be dependent on the constraints of the environment. This high level of sophistication for both the DHM and the environment are also critical in convincing workers, employers, and other stakeholders that the ergonomic assessment in question is valid. This modelling approach may also apply to other industries as well, including firefighting, where environmental scenarios can be imported into the analysis for discussions surrounding task strategy or tool/equipment design. Although Jack users can simulate firefighting postures either manually or with the supplementation of motion capture data, the software fails to have the versatility to account for external loads not applied to the hands, including the PPE. The PPE worn by firefighters (bunker gear ≈ 8.3 kg, helmet ≈ 1.7 kg, and self-contained breathing apparatus (SCBA) ≈ 17.5 kg) is expected to be an important consideration when tracking posture strategies or the biomechanical injury risks to which they are exposed. However, 3DSSPP (Center for Ergonomics, University of Michigan, Ann Arbor, MI, USA), which is a simplified version of Jack without certain features, such as the ability to stream motion capture data or the inclusion of sophisticated CAD drawings, has the ability to account for external loads acting on several joints, including the shoulder and low back. Although 3DSSPP does not have the ability to drive DHM postures with motion capture data, its ability to account for external loads is expected to be a significant benefit over Jack for assessing firefighter ergonomics of fire suppression tasks. However, no literature to date has explored the use of DHM software for conducting ergonomic evaluations of firefighters performing simulated fire suppression tasks with or without accounting for external loads associated with PPE.

Therefore, the purpose of this research is to provide insight into the development of a protocol for conducting ergonomic analyses of firefighters, inclusive of the loads caused by their PPE, using DHM tools and video observation from a Microsoft Kinect® system. To achieve this purpose, we first developed a method to account for the external loads placed on firefighters by their bunker gear and SCBA. We then compared and contrasted the use of two popular DHM software applications, Jack and 3DSSPP, and their embedded ergonomic tools, to evaluate the musculoskeletal injury risks associated with a common physically demanding firefighting task. A secondary analysis was conducted to determine if sex-based differences in the ergonomic tool existed between male and female firefighters within the cohort subset.

2. Methods

2.1 Overview

The current study was conducted in two phases: 1) biomechanical modeling of the external loads worn by the firefighters, including full bunker gear and a SCBA, and 2) posture simulation using a) Jack DHM software (v 8.3), and b) 3DSSPP DHM software. Data used to develop the models and the simulations were obtained from a subset of 12 participants (6 female) from a previous study where 48 firefighters (6 female) were asked to perform three common fire suppression tasks in a training facility while wearing full bunker gear and a SCBA (see Chapter 3). Only the initial hose pick-up phase of the high-rise pack lift and carry task from that investigation was examined in the current study.

Comparisons were made between the OWAS ergonomic assessments performed in the previous study with those obtained from the Jack DHM software. The OWAS tool is used to determine the urgency with which ergonomic action is needed to reduce the risk of musculoskeletal injury for the posture under investigation (Karhu et al., 1977). Four Action Classification (AC) scores are used for this purpose: 1) no action needed, 2) action needed in the near future, 3) action needed as quickly as possible, and 4) immediate action required.

Comparisons were also made between the Static Strength Prediction (SSP) output from the Jack and 3DSSPP DHM software for each of the postures assessed. The SSP ergonomic tool is one of several tools embedded in the Jack DHM software and is the foundational tool within the 3DSSPP DM software. The tool uses a static strength database to determine the percentage of the population that has the strength at each joint to meet the strength requirements of the task given their anthropometry and posture as well as the external loads imposed on the DHM (Don B. Chaffin & Erig, 1991). In the current study, these external loads included those placed in the hand during lifting of the high-rise pack, those distributed across the body from the bunker gear, and those acting at the trunk and shoulder joints due to the SCBA. The SSP tool also calculates the L_4-L_5 compression forces, which can be used as an indicator of low back injury risk using the NIOSH Action Limit (AL) (NIOSH, 1981).

2.2 Biomechanical modeling of external loads

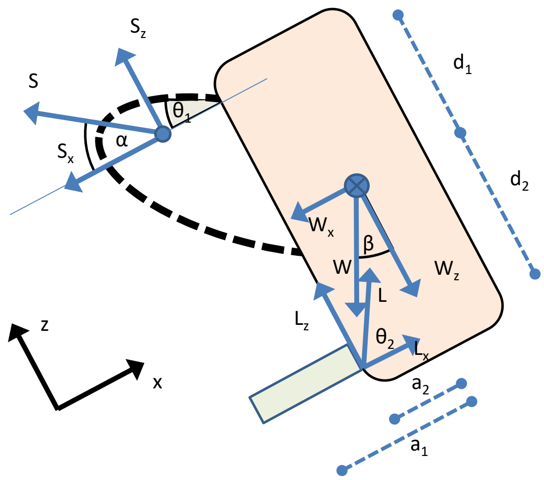
The biomechanical modeling of external loads was performed within the limitations of the two DHM tools used in Phase 2 of this study as well as with consideration towards ease of protocol reproducibility for future analyses. The two external forces that were considered in this study were: 1) the load due to the bunker gear, including pants, jacket, and gloves (total of approximately 8.3 kg), and 2) the load of the SCBA (17.5 kg). The load due to the helmet was not accounted for given that neither DHM tool had the capability of adding external loads to the head. For reasons described in the following section, the load due to the boots of the participants could not be considered in this study.

2.2.1 External loads caused by the bunker gear

The mass of the bunker gear was determined to be the average (8.3 kg) of an extra-small (7.67 kg) and a large (8.8kg) set of gear measured using an analog hanging scale. The rationale for using this average mass was based on the fact that, at the time of data collection, each person's bunker gear was not weighed separately nor was the size of their bunker gear recorded. Therefore, an individualized bunker gear load could not be determined for each participant. The distribution of load across the bunker gear was assumed to approximate the additional load on each human body segment caused by additional overall body mass for the same height. Therefore, the external forces due to the bunker gear load worn by the firefighters were approximated by adding 8.3 kg to the mass of each participant. As a result, the mass of each body segment likewise increased proportionately as a function of the anthropometric dataset used by the respective DHM software. The mass of the boots were excluded from this firefighter mass adjustment because: 1) boots have a mass of 5.1kg and would artificially increase the distribution of load to the rest of the body, and 2) the DHM software uses a top-down biomechanical modeling approach and, therefore, the mass of the feet do not play a role in the forces calculated above the ankles.

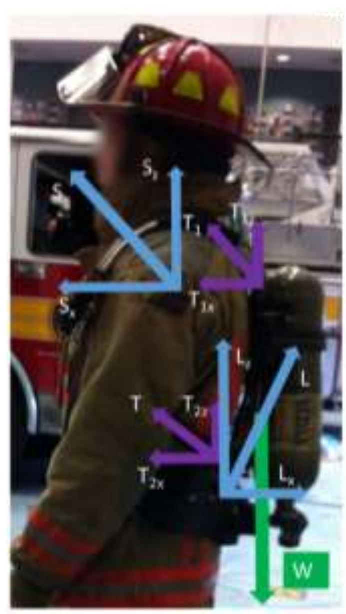
2.2.2. External loads caused by the SCBA

The 2D static biomechanical model (Figure 1) used to determine the external loads on the shoulders and low back due to the SCBA was derived from a load carriage model proposed by Pelot et al. (2000) and Bryant et al. (2000), and later simplified by (Kim, 2014). The original model (Appendix A) uses known tensions of the upper and lower shoulder straps as well as their orientations relative to the backpack to determine the reaction force at the shoulder joint. Likewise, tension of the waist belt was used to determine the shear and compression reaction forces of the lumbar spine. These tension variables were removed from the current model for reasons described below.



a)

b)



c)

Figure 1: a) Biomechanical model for backpacks derived from Pelot et al. (2000) that was modified to accommodate the available firefighter SCBA information. The b) dimension and c) angle inputs were derived largely from a sample firefighter in full bunker gear and SCBA. (Note: the distances, force vectors, and angles are not drawn to scale).

The following is a list of assumptions that were made in the development and implementation of the model: (Note: unless otherwise specified, references to x- and z-axis are for the local coordinate system shown in Figure 1a)

a) The x and z components of the shoulder reaction force are the sum of the respective tension components of the upper and lower shoulder straps (Equations 1 and 2). The net shoulder reaction force (S) can be calculated using Pythagoras' theorem (Equation 3). Thus, if the shoulder reaction force is known, or can be estimated or assumed, then it is not necessary to include the upper and lower strap tensions in the model when solving for net forces. However, given that the lower shoulder strap attaches below the center of mass of the SCBA, the tension on this strap causes a moment in the opposite direction to the upper shoulder strap. The moments about the center of mass of the SCBA caused by the tension in the straps are not accounted for in the proposed simplified model thereby inhibiting the model from being able to satisfy the condition of having zero net moment about the center of mass of the SCBA (equation 7).

Equation 1

$$S_z = T_1 sin\theta_1 + T_2 sin\theta_2$$

Equation 2

$$S_x = T_1 cos\theta_1 + T_2 cos\theta_2$$

Equation 3

$$S = \sqrt{(S_x)^2 + (S_z)^2}$$

b) The direction of the shoulder reaction force can be estimated using the following equation:

Equation 4

$$\alpha = 0.7451(\theta_1) + 10.749$$

This assumption is based on data shared by Bryant et al. (2000) and used to validate the 2D static biomechanical model by Pelot et al. (2000). Their data show that the angle between the upper strap and the x-axis (θ_1) is highly correlated (R^2= 0.97, p = 0.002) with the angle between the shoulder reaction force and the x-axis (α) based on the linear relationship shown in Equation 4. The relative upper strap angle (θ_1) was determined from an in-depth investigation of photographs from a sample firefighter (Figure 2) from the historic data set (see Chapter 3) of this thesis. We have also made the assumption that these two relative angles are constant regardless of trunk flexion angle.

c) The force of friction on both the shoulder and waist straps can be omitted from the model without significant impact. This assumption is based on the fact that any forces of friction within the system that need to be opposed to satisfy the force-related equations of static equilibrium should be accounted for in the net shoulder and lumbar reaction forces.

d) The distances from the center of mass of the SCBA to the center of the shoulder in the z-direction (d_1) and the x-direction (a_1) are constant between participants. The distance d_1 is also the same distance in the z-direction between the center of mass of the SCBA and the insertion point of the upper shoulder strap. These assumptions were determined from an in-depth investigation of photographs from a sample firefighter wearing full bunker gear in a neutral posture (Figure 1). Deviations in participant torso height and shoulder depth will alter the accuracy of this assumption; however, the accuracy with which these distances can be calculated is questionable given that the measurements must be made through several layers of clothing. Thus, for this purpose of this simplistic model, we assume distances d_1 and a_1 are constant.

e) The distances from the attachment point of the waist strap on the SCBA to the center of mass of the SCBA along the x-direction (a_2) and the z-direction (d_2) are constant given that they are part of the SCBA system and are not modifiable by the firefighters. These values were determined from measurements made from an in-depth investigation of photographs from a sample firefighter wearing full bunker gear in a neutral posture (Figure 1).

f) The global trunk flexion angle (β) can be determined through posture simulation using DHM software (e.g. Jack or 3DSSPP) by mapping the observed posture of a firefighter in an image to the DHM within the software.

The mass of the SCBA was determined using an analog hanging scale. This mass was multiplied by the acceleration due to gravity to determine the weight of the SCBA (W). The location of the center of mass of the SCBA in the sagittal plane was determined by taking three still images of the sagittal plane of the SCBA being hung by a rope, drawing vertical lines on these images starting at the vertical hanging rope and bisecting the SCBA, and then overlapping these images. The intersection of the lines was determined to be the center of mass along the sagittal plane. For the purpose of this exercise, and given the 2-dimensional nature of this analysis, it was assumed that the SCBA was symmetric between its right and left sides along the frontal plane. Thus, the images focused on identifying the center of mass in the vertical and anterior-posterior directions. A scaling factor was then applied to the images to determine the exact location of the center of mass.

The following equations of static equilibrium were used to develop the current biomechanical model:

Equation 5

$$\sum F_x = 0 = L_x - W \sin\beta - S\cos\alpha$$

Equation 6

$$\sum F_z = 0 = L_z - W \cos\beta + S\sin\alpha$$

Equation 7

$$\sum \tau = 0 = S_x(d_1) - S_z(a_1) + L_x(d_2) - L_z(a_2)$$

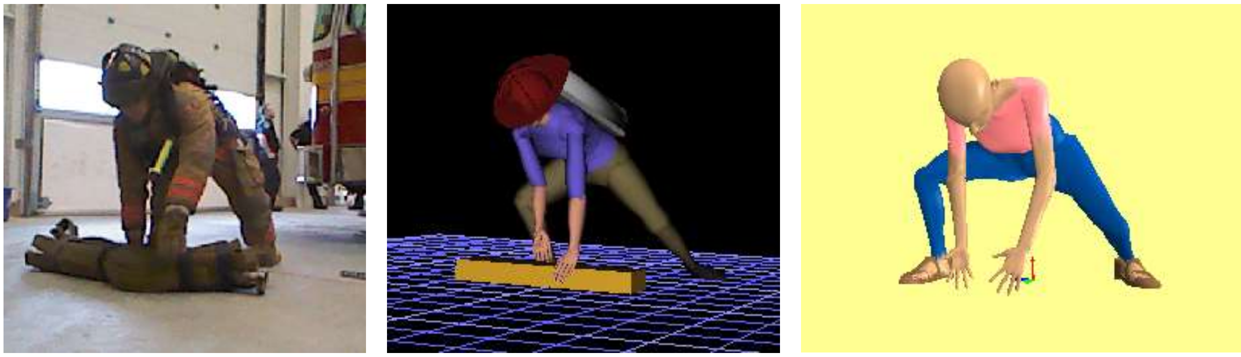
These equations were used to solve for the shoulder (S) and lumbar (L) reaction force using optimization criteria whereby the force distribution between the shoulder reaction force (S) and the lumbar lift force (L_z) is a ratio of 1:2 (Pelot et al., 2000). This assumption was derived based on expert opinion of load carriage modeling experts (Pelot et al., 1995) under the rationale that more of the lifting load should be placed on the waist rather than the shoulder.

The shoulder and lumbar reaction force magnitudes in the vertical and anterior-posterior directions were then used as inputs into the 3DSSPP DHM software for the purpose of better understanding how the SCBA affects the injury risks associated with the simulated high-rise pack lift and carry fire suppression task.

2.3 Posture simulation using DHM software

Two different DHM software tools, Jack and 3DSSPP, were used to evaluate the injury risk associated with the initial hose pick-up phase of a high-rise pack lift and carry task (Figure 2). An ergonomics expert with over eight years of experience using the Jack DHM software and nine years of experience using the 3DSSPP software performed the firefighter task simulations.

The data used to drive the simulations were collected as part of a previous study conducted on a cohort of 48 firefighters (see Chapter 3). Participant information and movement data from twelve of these firefighters were gathered. 100% of the women from the larger cohort were included in the subset of firefighters (n = 6, height = 167.7 cm ± 4.3, weight = 70.0 kg ± 12.6). The remaining six male firefighters were randomly selected (height = 183.3 cm ± 8.0, weight = 93.0 kg ± 11.9). The female firefighters were modeled using female DHMs and the male firefighters were modeled using male DHMs.



a) b) c)

Figure 2: Example of a) a female firefighter performing the initial hose pick-up of the high-rise pack lift and carry task being simulated in using b) the Jack DHM software (Jill is the female DHM) and c) the 3DSSPP DHM software.

2.3.1 DHM simulation data

The posture simulations performed in this study use a subset of data collected from a cohort of 48 firefighters who performed three common firefighting tasks: 1) hose drag, 2) hose pull, and 3) high-risk pack lift and carry (See Chapter 3). Twelve participants were selected from this cohort including all 6 female firefighters who originally participated as well as 6 randomly selected male firefighters. Sex, height, and weight data for each participant were used to customize the DHM anthropometry prior to posturing using each of the DHM software. For both DHM software, 8.3 kg of mass was added to the weight of each firefighter to account for the external load caused by the bunker gear.

The current analysis examined a single representative frame of the pick-up phase of the high-rise pack lift and carry task as this task phase was determined to be one of the most urgently in need of further ergonomic analysis based on the OWAS ergonomic tool (See Chapter 3). The movements of these firefighters were observed using a Microsoft Kinect® motion capture system (Microsoft for Windows v1) collected at 30 Hz. The Microsoft Kinect® system provided three data outputs: 1) the colour (RGB) video data at 1280 x 960 resolution, 2) 3D infrared depth sensor data, 3) skeletal tracking of 20 joints (see Appendix C). Simulations with the Jack DHM software used all three outputs while simulations with the 3DSSPP DHM software used only the video and depth sensor data.

2.3.2 Posture simulation in Jack DHM software

Jack DHMs can be postured either using manual manipulation of the joints to achieve the desired posture or by streaming video capture data, including Microsoft Kinect® skeletal tracking data, into the software to drive the skeletons of the manikins into the desired postures (Kajaks et al., 2011). For the current study, a hybrid approach was used whereby the simulations started by driving the postures using the Microsoft Kinect® data and were finalized using manual manipulation based on images from the Microsoft Kinect® video and depth data. This hybrid approach was necessary because of the known inconsistencies in the Kinect skeletal tracking capabilities of the Microsoft Kinect® for Windows v1, particularly when the person in the field-of-view does not have their frontal plane square with the camera and is thereby occluding their own body segments and rendering some or all of the skeleton data temporarily unavailable (Bonnechere et al., 2014).

The steps involved in using the Jack DHM software to simulate a representative static posture associated with the initial hose contact phase of the high-rise pack lift and carry task include:

1) Assign the firefighter's sex, height, and weight to each DHM, where the weight was adjusted to include an additional 8.3 kg to account for the bunker gear worn.
2) Import objects including a firefighter helmet and basic representations of the SCBA pack and high-rise pack were included in the simulation (Figure 2) (Note: these objects were included for visual purposes only)
3) Run Kinect Studio from the Microsoft Kinect® for Windows Software Development Kit v1.8 and load the desired pre-recorded data. Connect the Microsoft Kinect® device to both Microsoft Kinect® studio and to Jack motion capture module.
4) Map the Microsoft Kinect® skeleton onto the Jack skeleton.
5) Play the desired high-rise pack lift and carry trial until the initial hose contact phase is reached.
6) Disconnect the Microsoft Kinect® skeleton from the Jack skeleton and continue to posture the Jack DHM manually until the desired posture is reached using the "Human Behaviour" and "Human Control" modules. These modules limit the postural options of the DHM to those that are within the typical human range of motion. A combination of the Microsoft Kinect® video

data and depth data were used to obtain the visual postural information needed to manually complete the simulations.

7) Input the estimated hand loads, where the weight of the 19.5 kg high-rise pack was frequently divided evenly between to the hands (95.65 N in each hand) unless one hand was clearly supporting more of the load, in which case 75 % of the load was in one hand and 25 % was in the other hand.
8) Run the OWAS and SSP ergonomic tools and export the OWAS, percent capable, and L_4-L_5 compression force results.

2.3.3 Posture simulation in 3DSSPP DHM software

Unlike with the Jack DHM software, the 3DSSPP DHM software is dependent on manual manipulation to posture the DHMs appropriately. 3DSSPP does have a selection of pre-set postures that facilitate the start of the posture simulation process; however, the bulk of the posturing must happen manually.

The steps involved in using the 3DSSPP DHM software to simulate a representative static posture associated with the initial hose contact phase of the high-rise pack lift and carry task include:

1) Assign the firefighter's sex, height, and weight to each DHM, where the weight was adjusted to include an additional 8.3 kg to account for the bunker gear worn.

2) Posture the 3DSSPP DHM manually by moving the joint centers in one of three fields-of-view accordingly until the desired posture is reached, starting from the lower extremities and moving upwards on the body (Figure 3). The Microsoft Kinect® video and depth data were used to gather the information needed to perform the posturing.
3) Determine the trunk flexion angle from the posture report and input this value into the SCBA biomechanical model.
4) Determine the horizontal and vertical components of the lumbar and shoulder joint reaction forces in the global coordinate system. The model outputs these forces in the local coordinate system assigned to the SCBA. Thus, the force components must be rotated by the trunk angle in order to be presented in the global coordinate system prior to being included in the 3DSSPP DHM software. The equal and opposite of these lumbar and shoulder joint reaction forces were then utilized as the external loads acting on the low back and shoulder joints, respectively. It is important to note that the shoulder force calculated from the 2D SCBA biomechanical model was divided equally between the right and left shoulders upon implementation in the 3DSSPP DHM.
5) Input the estimated hand loads used during the Jack simulations.
6) Export the report for the SSP analysis of the DHM both with and without the external loads caused by wearing the SCBA.

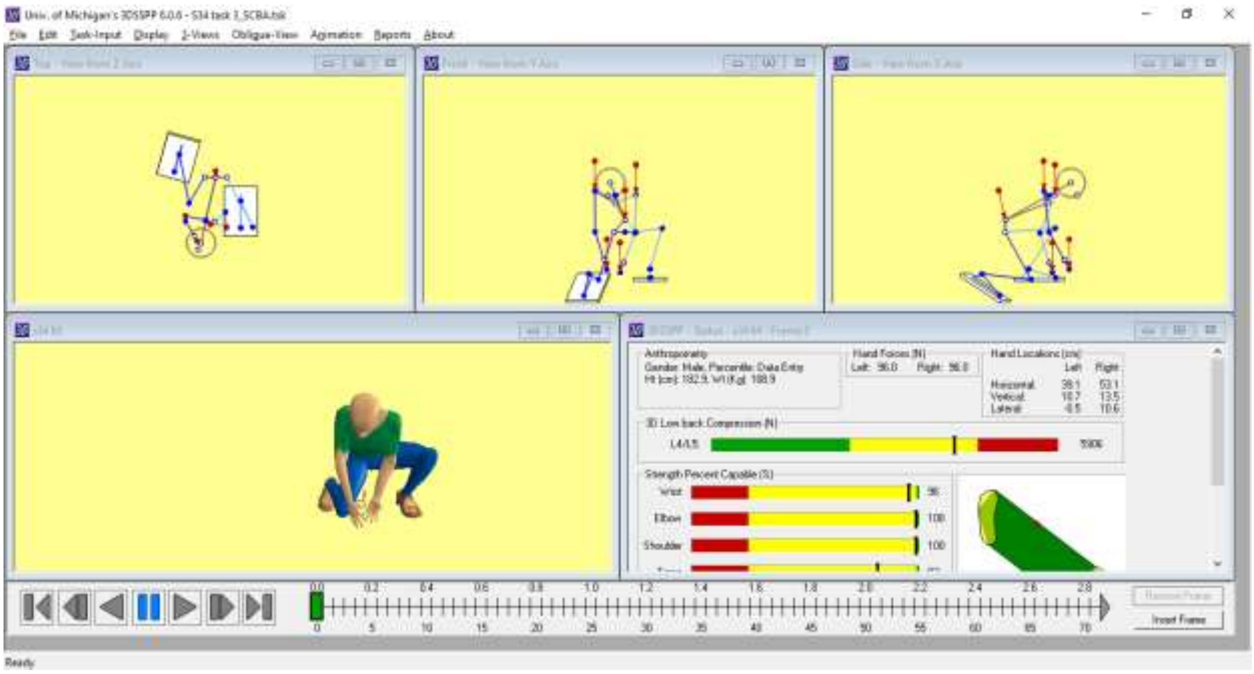


Figure 3: Screen capture of the 3DSSPP interface showing the three fields-of-view where posture manipulation is performed by moving the solid blue joint centers into the desired location.

2.3.4 Ergonomic assessment tools

The OWAS ergonomic tool uses a full-body posture binning approach to determine if ergonomic action is needed to improve a posture based on one of four Action Classification (AC) scores: 1) no action is needed, 2) action is needed in the near future, 3) action is needed as quickly as possible, or 4) immediate action is required (See Chapter 3 for more information about the OWAS Ergonomic Tool).

The SSP tool outputs the minimum percent capable for strength and the L_4-L_5 compression force. The minimum percent capable for strength is the foundational component of the SSP ergonomic tool. The tool calculates moments about the main joints of the body from postural, anthropometric, and external load data and compares these moments against a strength database for each joint to determine the percentage of the population that could safely perform the task using the given posture (Don B. Chaffin & Erig, 1991). For a task to be considered safe, the tool proposes that 75% of the population should have the strength to perform a given task using the evaluated posture. The minimum percent capable value across all joints is used as the limiting factor and, therefore, serves as the value that determines whether or not the observed posture places the worker at undue risk of injury.

The L_4-L_5 compression force calculated within the DHM software is based on the posture under evaluation, worker anthropometry, and the external loads on the work. The calculated compression force can then be compared with the NIOSH Action Limit of 3400 N. A compression force greater than 3400 N indicates that the posture should be altered as it places more than 25% of female workers and 1% of male workers at a heightened risk of low back injury (NIOSH, 1981).

2.4 Data Analysis

2.4.1 SCBA Biomechanical Model Outputs

The shoulder and lumbar reaction forces calculated using the SCBA biomechanical model were evaluated based on the acceptability limits determined by Bryant et al. (2000). These limits state that the maximum acceptable lumbar force (L_x) acting perpendicular to the pack should be 135N and the maximum acceptable shoulder reaction force (S) should be 290 N. This assumption was based on perceived discomfort data collected from 20 soldiers following a 6 km march wearing 32 kg backpacks (Bryant et al., 2000). The results of the SCBA biomechanical model output evaluation were reported as either being acceptable or unacceptable for each posture assessed using the 3DSSPP software.

2.4.2 Simulation Ergonomic Tool Comparisons

The Jack DHM software analyses yielded ergonomic assessment results for the OWAS and SSP ergonomic tools while the 3DSSPP DHM software provided results only for the SSP ergonomic tool. L_4-L_5 compression forces were included as part of the SSP tool in both software applications.

The results from the Jack OWAS AC scores were compared to the previously conducted manual OWAS AC evaluation (Chapter 3). This comparison, which was done using the Wilcoxon Signed Ranks Test, was used as a measure to inform the validity of the Jack DHM software simulations. For the purpose of determining overall posture acceptability, only those postures with an AC score of 1, where no ergonomic action is required, were considered acceptable.

The SSP results for the minimum percent capable for strength and the L_4-L_5 compression force from the Jack analysis were compared against the results of the 3DSSPP analyses both with and without the external loads due to the SCBA. The results from the two 3DSSPP analyses were also compared. These analyses were done using a mixed analysis of variance (ANOVA) with repeated measures.

The overall posture acceptability ratings for all three tools, where an assessment is deemed either acceptable or unacceptable based on specific criteria for each ergonomics tool, were compared using the Cochrane's Q-test. Where necessary, and as a post-hoc test following the omnibus Cochrane's Q-test, McNemar's Test was used for two-group comparisons. An evaluation criterion of 75% was used to determine the posture acceptability for the minimum percent capable evaluation, whereby the postures that were reported to have a minimum percent capable of 75 % or greater were considered acceptable. The NIOSH safe lifting AL uses an evaluation criterion of 3400 N of L_4-L_5 compression forces to determine posture acceptability (NIOSH, 1981), with the posture being deemed acceptable if the L_4-L_5 compression force was below the AL limit.

3. Results

3.1 SCBA Biomechanical model outputs

For all participants, the calculated lumbar lift reaction force (Lz) and the shoulder net joint reaction force were within the acceptable limits of 135 N and 290 N, respectively. The average lumbar lift reaction force was 60.9 N (SD = 38.9) while the average net shoulder reaction force was 30.4 N (SD = 19.5). A complete set of model inputs (Table B.1) and outputs (Table B.2) are shown in Appendix B.

3.2 Ergonomic tool comparisons

A comparison of the manually obtained OWAS AC scores from the previous study with the OWAS AC scores output by the Jack DHM software showed no differences ($p = 0.276$). The median score for the manual OWAS method was 3.0 and the median score for the Jack OWAS method was 3.5. These median scores imply that ergonomic action is needed either as quickly as possible (AC score of 3) or immediately (AC score of 4), respectively.

The results of the repeated measures ANOVA to examine differences in the minimum percent capable analyses between the DHM software evaluations show a main effect for the evaluation method ($F(2,20) = 23.676$, $p < 0.001$), with sphericity assumed, and no effect for sex ($F(1,10)=2.028$, $p=0.185$). The pairwise comparison for evaluation method shows that the Jack method yields greater minimum percent capable scores than does the 3DSSPP method without the SCBA loads ($p = 0.006$) and with the SCBA loads ($p = 0.001$). The 3DSSPP method with the SCBA reported the lowest minimum percent capable scores (3DSSPP (no SCBA) vs. 3DSSPP (with SCBA): $p = 0.024$). Table 1 shows the individual firefighter results for each of the minimum percent capable evaluations performed, including the limiting joint for each posture assessed. The hip was most often the limiting joint in the two methods where the SCBA loads were not included while the knee was the primary limiting factor when the SCBA loads were included in the evaluation.

The results of the repeated measures ANOVA to examine differences in the calculated L_4-L_5 compression forces between the three DHM software evaluations show a main effect for the evaluation method ($F(1.08, 10.76) = 15.09$, $p = 0.002$) with Greenhouse-Geisser correction (Figure 4). The post hoc analysis revealed that Jack simulations had the lowest compression forces (Jack vs. 3DSSPP (no SCBA): $p = 0.013$, Jack vs. 3DSSPP (with SCBA): $p = 0.008$), with compression forces being the greatest in the 3DSSPP simulations that included the external loads due to the SCBA (3DSSPP (no SCBA) vs. 3DSSPP (with SCBA): $p = 0.010$). A main effect for sex ($F(1,10) = 653.87$, $p<0.001$) was also found, where females had significantly lower compression forces compared to male firefighters.

Table 1: Descriptive results from the minimum percent capable evaluations from each of the three evaluation methods.

		Jack Output		3DSSPP Output without the SCBA Loads		3DSSPP Output with the SCBA Loads	
Subject Number	Sex	Minimum % Capable	Limiting Joint	Minimum % Capable	Limiting Joint	Minimum % Capable	Limiting Joint
1	Female	70	Shoulder	72	Hip	38	Knee
2	Female	86	Wrist	57	Hip	39	Knee
3	Female	86	Wrist	38	Knee	8	Knee
4	Female	16	Hip	0	Ankle	0	Ankle
5	Female	84	Shoulder	80	Hip	71	Knee
6	Female	57	Hip	1	Hip	0	Ankle
7	Male	92	Hip	63	Hip	51	Hip
8	Male	85	Hip	74	Hip	73	Hip
9	Male	86	torso	30	Hip	20	Hip
10	Male	89	Hip	77	Ankle	76	Hip
11	Male	87	Knee	37	Hip	25	Hip
12	Male	77	Hip	66	Hip	23	Knee
Average (SD)		76.3 (21.3)		49.7 (28.1)		35.2 (27.6)	

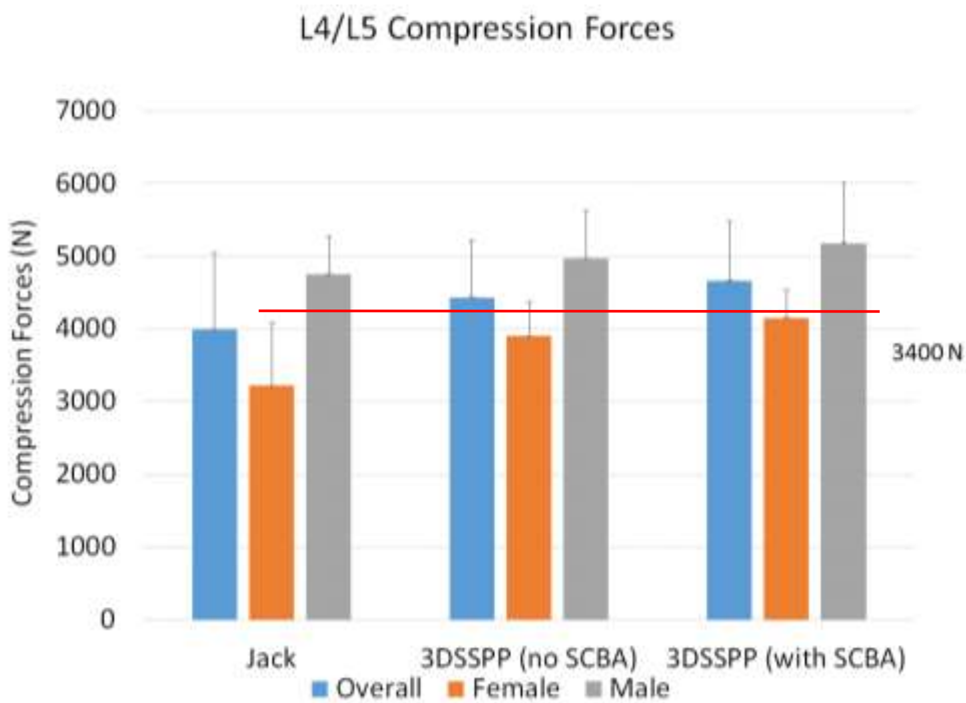


Figure 4: L_4-L_5 lumbar compression forces determined using each of the three evaluation methods displayed as the mean and standard deviation for the full sample population as well as divided by sex. The NIOSH AL limit of 3400 N is also displayed.

The overall posture acceptability for each ergonomics tool and DHM software are shown in Table 2. This table provides summary data indicating the percentage of assessments that were deemed acceptable in accordance with the thresholds of the ergonomic tools used. The OWAS evaluations were both in agreement that 0 % of the assessments were acceptable. The Cochrane's Q-test shows differences between the minimum percent capable evaluations (p = 0.001), with posture acceptability rates of 75% for the Jack analyses, 17% for the 3DSSPP analyses with no SCBA and 0% for the 3DSSPP analyses with the SCBA modeled. However, no significant differences existed between the three L_4-L_5 compression force evaluations ($p = 0.097$). When compared within each evaluation software program the results from the McNemar's analysis showed no difference between each set of 3DSSPP results. However, significant differences were found between the Jack minimum percent capable and the L_4-L_5 compression force evaluations ($p = 0.031$), as well as between the Jack OWAS and the minimum percent capable evaluations ($p = 0.004$).

Table 2: Percent of postures deemed acceptable based on overall OWAS AC Score, percent strength capability from the SSP tool, and NIOSH AL for the L4/L5 Compression Forces.

	Percent Posture Acceptability							
	OWAS AC Score		Overall Percent Strength Capablility			NIOSH AL		
	Manual	Jack	Jack	3DSSPP (no SCBA)	3DSSPP (SCBA)	Jack	3DSSPP (no SCBA)	3DSSPP (SCBA)
Overall	0	0	75	17	8	25	8	0
Female	0	0	50	17	0	50	17	0
Male	0	0	100	17	17	0	0	0

4. Discussion:

4.1 Biomechanical Modeling

Simplified recommendations were proposed to account for the weight of the bunker gear in the Jack and 3DSSPP DHM software and the SCBA in the 3DSSPP DHM software.

Neither DHM software had the capability to account for the external load caused by the helmet. The bunker gear was assumed to have a mass distribution that resembled the distribution of load within the anthropometric databases used by the Jack (Army Anthropometric Survey (ANSUR)) and 3DSSPP (National Health and Nutrition Examination Survey (NHANES)) DHM software. The validity of this assumption requires further testing. For instance, the presence of tools or equipment within the pockets of the bunker gear may affect the load distribution of the entire gear. Furthermore, a constant mass of 8.3kg was used to account for the bunker gear worn by all firefighters, excluding the boots and helmet. This mass is expected to change as a function of bunker gear size, where sizing is a customizable feature for firefighters, and is likely to be directly proportional to firefighter anthropometry. Therefore, future work should investigate the relationship between bunker gear mass and firefighter anthropometry, with the goal of developing a simple equation that can be easily implemented to estimate the firefighter-specific bunker gear mass.

The biomechanical model used to estimate the loads on the shoulder and low back due to the SCBA was based on a combination of load carriage models (Perlot et al., 1995; Kim, 2014) that have been simplified to facilitate the known information about the SCBA. The model was used to estimate the shoulder and lumbar reaction forces, which were then used as inputs in posture simulations using the 3DSSPP DHM software. When compared against discomfort criteria for shoulder and lumbar strap forces (Bryant et al., 2000), the model’s net shoulder and vertical lumbar reaction forces were well below the cut-off criteria of 290 N and 135 N, respectively. This finding is supported by data from Bryant et al. (2000) who examined the load distributions of five military packs ranging in mass from 31.8 kg to 33.1 kg at trunk angles between 17.6 degrees and 26.5 degrees. With pack masses that were over 1.8 times the SCBA mass, their estimates for net shoulder (319.3 N ± 30.5) and vertical lumbar (205.26 N ± 29.0) joint reaction forces are expectedly greater. However, the shoulder and lumbar reaction force results of the current study are considerably lower, even after taking into consideration the decreased load and increased trunk inclination angles. This suggests that our model may be under-estimating the actual joint reaction forces. Two reasons for this may be: 1) the omission of frictional forces and 2) the omission of the contribution of the lower shoulder strap to the model. In excluding the lower shoulder strap from the model, we were unable to solve for the third equation of static equilibrium whereby the net moment of the system acting about the center of mass of the SCBA is supposed to equal zero. The moment contribution of the lower shoulder strap about the SCBA center of mass is in the opposite direction to that of the upper shoulder strap and the lumbar strap. This means that any moment caused by the lower shoulder strap must be counteracted by either the upper shoulder strap or the lumbar strap. By omitting the moment contribution from the lower shoulder strap we are effectively lowering the required moments of the lumbar strap and upper shoulder strap and, consequently, decreasing the net lumbar and shoulder reaction forces. Therefore, future work should examine ways of including the force contributions of both the upper and lower shoulder straps in the model.

Additionally, the model makes several assumptions about the properties of the SCBA, including left and right symmetry, constant relative upper strap angles regardless of trunk angle or firefighter characteristics, and constant dimensions between the location of the center of mass and the relevant firefighter landmarks (e.g. shoulder joint center). The assumption of left and right SCBA symmetry is necessary for the 2D model used. However, future work can inform the development a 3D model that accommodates not only the medio-lateral distribution of load from the SCBA but also how this load is distributed across the torso when a firefighter is using an asymmetric posture. In the current application of the model, firefighter symmetry was assumed given that the postures observed generally used two hands for pick-up, with the load centered medio-laterally in front of the firefighters.

Customizing the dimensions between the center of mass and firefighter anatomical landmarks, such as the shoulder joint center and L_4-L_5 joint, is also an important next step. Measuring these distances physically on each firefighter or from sagittal plane images may not be sufficient given the multiple layers of gear worn over top of these anatomical landmarks. A more simplistic method might be to use a regression equation based on anthropometric databases. This method might allow for easier implementation of the future model given that anthropometric measures are already an input in the model.

The current model uses a traditional free-body diagram approach to estimate the shoulder and lumbar joint reaction forces. This method is commonly used in load carriage research (e.g. Bryant et al., 2000; Kim, 2014; and Perlot et al., 1995). An important benefit to this method is its ease of implementation within the 3DSSPP DHM software where the shoulder and lumbar joint reaction forces from the model are directly related to the respective external force inputs required by the DHM software. However, this model fails to account for the contact force between the SCBA and the trunk itself. Likewise, the 3DSSPP software is unable to account for this force contribution. As the trunk increases in inclination, the contribution of this contact force acting on the trunk is expected to increase while the external forces acting at the shoulder and lumbar regions are expected to decrease. However, this trade-off cannot be considered in the current model, nor can it be accounted for in the 3DSSPP software. To better understand the relationship of the contact force between the trunk and SCBA, data collection with more sophisticated instrumentation is required. Additionally, more versatile and customizable DHM software is needed in order to account for this contact force. Future work should consider using more advanced instrumentation, such as pressure maps, strain gauges, and load cells to measure the direct loads on the body, particularly at the more extreme trunk angles used by firefighters in comparison to those typically studied in military-based load carriage research (e.g. Bryant et al., 2000).

Overall, the proposed SCBA model is a simplistic method of accounting for at least some of the external load contributions of the SCBA, and is an important first step in conducting in-depth ergonomic analyses of firefighter tasks using DHM software.

4.2 DHM software assessments

4.2.1 Comparison of evaluation methods

The non-significant difference between the previously performed manual OWAS assessment (see Chapter 3) and the current Jack OWAS assessment signifies that: 1) the simulation process within Jack yielded similar postures in accordance with the OWAS posture binning rubric, and 2) there is consensus from two OWAS approaches that the postures performed by the selected firefighters are in need of ergonomic action as quickly as possible. Although it is reasonable to expect some amount of error due to the skeletal tracking limitations by the Microsoft Kinect® (Diego-mas & Alcaide-Marzal, 2014; Ray & Teizer, 2012) and the innate subjectivity of the manual manipulation method (Kajaks et al., 2011; Lämkull et al., 2006) we have evidence that the firefighter simulations within the Jack DHM software were successfully performed using this hybrid approach.

Comparisons of the 3DSSPP and Jack DHM software were made using outputs from the SSP tool and the $L_4 – L_5$ compression forces, which are common tools to both software. The hypothesis was that the Jack SSP and L_4-L_5 compression force outputs were expected to be comparable to the equivalent outputs from 3DSSPP when the SCBA was not included in the model. However, the results show that the Jack SSP outputs were less conservative, or identified fewer risks, than the output from the 3DSSPP DHM software. The reason for this difference may be improved posturing within Jack both because of the hybrid approach where the motion capture data was supplemented by the manual manipulation method. Alternatively, the Jack DHM may have been more accurately postured because, as was reported by (Bush et al., 2012), Jack has both a more user-friendly manual manipulation interface as well as having more controls built into the software to prevent unrealistic movements. Thus, it is possible that the outputs from the 3DSSPP DHM software reported unrealistic injury risks due to inaccurate DHM posturing. A closer examination of the data in Table 1 suggests that this may be the case, where excessively low percent capable scores were reported for a number of the participants at the hip, knee, and ankle joints. It is also important to note that the final SSP output for a given assessment is dependent on the minimum percent capable across all joints for the DHM. Consequently, if only one joint is incorrectly postured and this joint yields the lowest percent capable score, then the entire posture is labeled with an SSP score that may be incorrectly lower.

From a worker's health perspective, having more conservative ergonomic assessment results is better than failing to identify possible injury risks; however, it is also important to ensure that the DHM postures being evaluated are as accurate as possible. Given that the hybrid posturing methods using the Jack software are more comprehensive, and the fact that the Jack ergonomic assessments was able to flag unacceptable postures, we feel that Jack is a more favourable tool for analyses where external loads, such as those caused by the SCBA, are not included. Unfortunately, a significant limitation to Jack is that it is not capable of accounting for external loads. Therefore, between the two DHM software evaluated, we are dependent on 3DSSPP to understand the impact of external loads caused by PPE such as the SCBA.

4.2.2. Impact of SCBA loading on ergonomic tool outputs

A comparison of the two 3DSSPP methods showed that more conservative ergonomics output scores were obtained after accounting for the external loads from the SCBA. However, the overall percent posture acceptability between the two 3DSSPP methods was not statistically different. This is perhaps due to the percent acceptability for both methods being very low, with a maximum of 17% of assessments being deemed acceptable when the SCBA loads were not included and no assessments being deemed acceptable when the SCBA loads were included. Nonetheless, the decrease in the minimum percent capable scores and higher L_4 – L_5 compression forces when the SCBA loads were added to the 3DSSPP model indicates that, as expected, the postures became more dangerous, with the risk of injury increasing. This highlights the importance of accounting for external loads, where possible within the limitations of the software.

4.2.3. Ergonomic assessments implications

The SSP and L_4-L_5 compression force analyses from both the Jack and 3DSSPP DHM software have allowed for an in-depth investigation of the injury risks involved in firefighters performing the initial hose contact phase of the high-rise pack lift and carry task. The results of the SSP and L_4-L_5 compression force analyses corroborate with the OWAS AC scores indicating that ergonomic action is needed as soon as possible in order to reduce the injury risks associated with performing this task. While 75% of the Jack assessments were deemed acceptable by the SSP ergonomic tool, only 25% of the firefighters could safely perform the task according to the L_4-L_5 compression forces. Based on the more conservative 3DSSPP DHM software, an average of 17 % and 8 % of firefighters were using safe postures to complete the task according to the SSP and L_4-L_5 compression force analyses, respectively. A closer investigation of the overall SSP results shows that most limiting joints were from the lower extremities. This finding, alongside the number of assessments that were deemed unacceptable by the L_4-L_5 compression force analyses, agrees with firefighter injury reports whereby the low back (32.1 %) and knee (22.6 %) are the two most frequently injured sites, with the shoulder joint (14.5%)

being the next most frequently injured site (Frost et al., 2016). Hence, the potential for higher injury risks to the low back and lower extremities given the inclusion of the SCBA loads in the 3DSSPP method are due to the increase in load above these joints in the kinetic chain. Intuitively, a load carried over the trunk must also be supported by the legs, which will contribute to the injury risk experienced by these joints.

A secondary purpose of this research was to understand the impact of sex on the ergonomic outputs and overall injury risks for the initial contact phase of the high-rise pack lift and carry task. The ergonomic tools used in this study are highly dependent on variables that are known to be influenced by sex, including height, weight, and strength (Fryar et al., 2012; Rohmert & Jenik, 1971). The results, which show reduced injury risks for the low back and no significant difference for percent capable scores for females compared to males, are contrary to the general hypothesis that females, given their smaller statures and reduced strength, are at greater risk of injury. In fact, the results of this study suggest that female firefighters may actually adopt postures that are more protective with respect to injury risks than their male counterparts. It is important to note, however, that a small sample of six female and six males were used, and only one phase of a single task was examined. More in-depth biomechanical analyses, however, is needed to further test if female firefighters tend to use safer postures across the breadth of tasks they perform.

4.3 Limitations

Many of the practical limitations to this study with respect to biomechanical models and DHM software have been previously described in their respective sections of this paper. However, the general limitations to the study design and DHM software, that warrant further discussion, are described herein.

Firstly, a small subset of 12 firefighters from a larger cohort of 48 were selected for this study. The small sample size used was justified given the purpose of the study, which was to provide insight into the development of a protocol for using DHM tools to conduct ergonomic assessments of firefighters that include the external loads due to their PPE. With this objective, a large sample was not necessary. However, the small sample size contributes to our decision not to apply a Bonferroni correction in our statistical analysis. There is currently a debate in the literature regarding the utility of the Bonferroni correction (Armstrong, 2014; Cabin & Mitchell, 2000). We opted not to use the Bonferroni correction for risk of making a type II error and for fear of becoming under-powered given the small sample size. Furthermore, as recommended by Armstrong (2014), a Bonferroni correction should be considered if many statistical tests are conducted without a "preplanned" hypothesis. This was not the case in the current study, where all statistical tests were planned.

Further rationale for the selected sample size includes the subject matter and methodology employed. The sample size used is customary for in-depth ergonomic analyses, such as those performed in the current study, because of the time requirements necessary to perform DHM simulations (Lämkull et al., 2006). Lamkull et al. (2006) asked participants with an average of 4.6 years of experience to complete a complex simulation in RAMSIS (Intrinsys Intelligent Engineering, Buckinghamshire, UK), which is a popular automotive manufacturing DHM software similar to Jack. The average time to completion was 30.05 min ±13.90 min. Although the time to complete a simulation was not recorded in the current study, the time investment to simulate the twelve firefighters using all three DHM simulation methods was substantial. Ideally, the Microsoft Kinect® data streaming process into Jack would have expedited the DHM posturing process; however, the necessity for substantial manual manipulation given the skeletal tracking limitations resulted in a significant time commitment for DHM posturing.

The study design only used one expert DHM simulator who conducted a single simulation of each firefighter for each of the three simulation methods tested. As a result, neither inter- nor intra-rater reliability could be determined. Having multiple raters or multiple trials per condition from which to calculate a mean output may have improved the accuracy of the results. Indeed, Lamkull et al. (2006) reported intra- and inter-rater differences following manual manipulation of the RAMSIS DHM that ranged between 1 and 22 degrees of standard deviation depending on the expert simulator and the joint for intra-rater differences and between 9 to 112 degrees depending on the joint for inter-rater differences. Thus, it may have been helpful to have multiple trials for averaging, particularly for the more challenging 3DSSPP simulations.

An advantage to using the hybrid approach to DHM simulations within Jack was that we were able to benefit from the skeletal tracking capabilities of the Microsoft Kinect®

system. However, a limitation to using this skeletal tracking data is that the accuracy of this data from participants wearing bulky clothing, such as the firefighter bunker gear, is unknown. To date, most studies focusing on testing the accuracy of the skeletal tracking capabilities of the Microsoft Kinect® system have examined simple postures in controlled environments with participants wearing minimal clothing (e.g. Bonnechere et al., 2014; Clark et al., 2012). As part of the development of a protocol that streams Microsoft Kinect® data collected from firefighters in full bunker gear into DHM software, the accuracy of the skeletal tracking should be investigated. However, in the current study, any potential inaccuracies in the Microsoft Kinect® skeletal tracking would have been corrected in the manual manipulation portion of the hybrid DHM simulation process.

A final limitation is not specific to the methods but rather is applicable to the current state of ergonomics research. The current study focused on the ergonomic assessment of a static posture used at a single moment of time. This was necessary because of the limitations of the tools themselves whereby dynamic movements and inertial properties of objects cannot be accounted for. The consideration of inertial properties becomes more important as loads become heavier, more malleable, and more awkwardly shaped. A firefighter raising a high-rise pack onto his/her shoulder is a prime example of where a dynamic ergonomic tool would be beneficial to account for the inertial properties of the hand load. Unfortunately, the current state of ergonomic tools limits us to conducting static analyses.

4.4 Implications and future directions for using DHM software for firefighter ergonomics

The current study proposes a simplified biomechanical model of an SCBA pack as well as a method for implementing the model in DHM software. The study also describes the strengths and limitations of two commonly used DHM software, Jack and 3DSSPP. Jack is arguably the more advanced of the two applications, with a larger suite of ergonomic tools, easier manual joint manipulation, and the ability to drive the DHMs with motion capture data including data recorded using a Microsoft Kinect® system. However, Jack's primary drawback for the purpose of firefighter ergonomics is its inability to account for external loads other than those acting on the hands or on the lower extremities due to leaning. Thus, we are limited to using the more primitive 3DSSPP in order to model the important SCBA loads acting on the low back and shoulders. Unfortunately, other external loads, such as that caused by the helmet, cannot be modeled in 3DSSPP. So, at best, using 3DSSPPP we can only understand a portion of the external loads impacting the injury risks exposed to firefighters during their manual materials handling tasks.

However, Jack appears to have the foundation necessary to be able to include the external loads at various body locations. Furthermore, Jack also has the ability to import CAD objects and assign inertial properties including mass, location of the center of mass, and dimensions. These imported objects can also be fixed to the DHMs so that they may maintain their orientation with the segment to which they are fixed as the body segment rotates. With these capabilities already in place, we are hopeful that the ability to model external loads, including the firefighter SCBA, and helmet, will be possible in the future. External loads due to the boots should also be considered in the future when using DHM simulation given their contribution to postural instability and fatigue (Garner et al., 2013; Park et al., 2015)

The ease-of-use and portability of the Microsoft Kinect® system make it an ideal tool for collecting motion capture data in the field. Eventually, as the technology improves, the Microsoft System may be able to independently and accurately drive the DHM in software, such as Jack, without the need for manual adjustments by an experienced ergonomist. With a protocol in place to easily account for the external loads due to the PPE that are acting on the firefighters, it is feasible that the combination of the Microsoft Kinect system paired with DHM software may be useful not only as an ergonomic assessment tool, but also as a training tool where firefighters can see their actions and the injury risks associated with them. Firefighters could then use this as an interactive tool to help them learn safer task completion strategies. This type of motor learning approach has already been demonstrated in the areas of physical rehabilitation (e.g. Vernadakis et al., 2014) and sport coaching (e.g. Kumada et al., 2013). With the speed of technological improvements in the field of markerless motion capture and DHM software, there is great potential for this kind of innovative technology to have an important impact in the area firefighter ergonomics.

5. Conclusion

This study provides important insights into the strengths, limitations, and considerations needed for conducting ergonomic analyses of firefighters using DHM tools and video observation from the Microsoft Kinect® system. The study also demonstrates the high injury risk associated with firefighters lifting a high-rise pack up off the ground, and the importance of the external loads due to the SCBA in quantifying these injury risks. More work is needed to understand the musculoskeletal injury risks of firefighters during real and simulated fire suppression tasks. This information can then be used to develop effective ergonomic training programs for firefighters for both junior and more experienced firefighters, as well as inform policy related to occupational health and safety.

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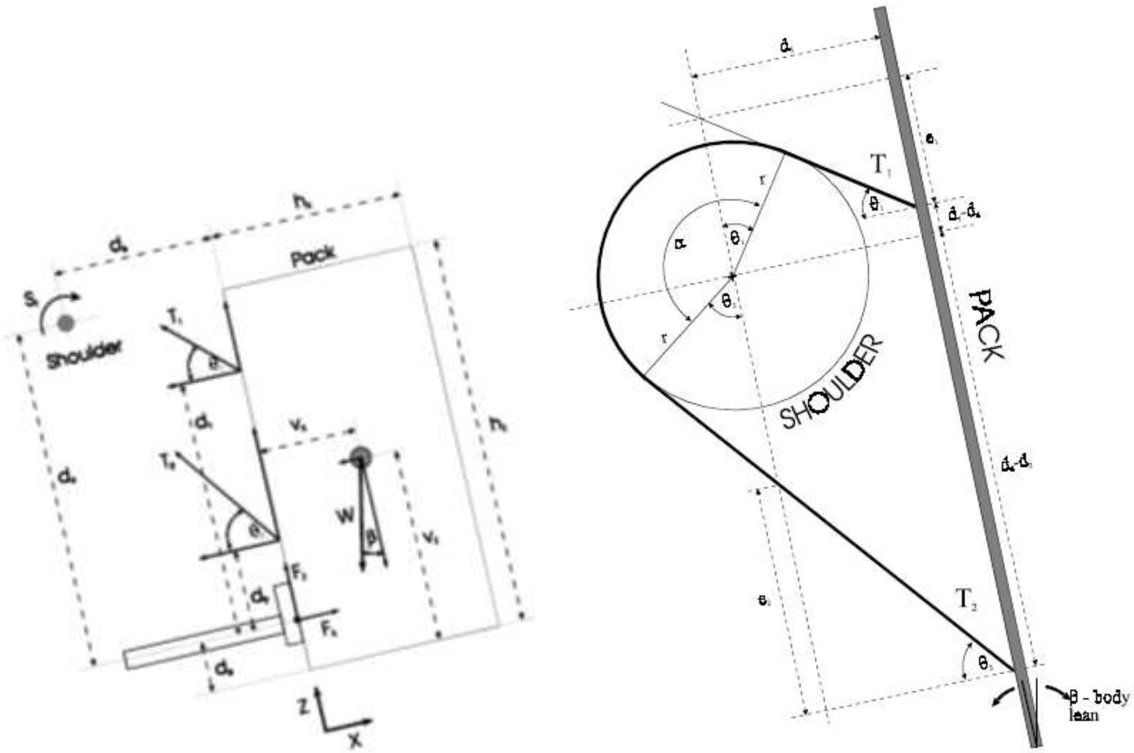
Appendix A: Military load carriage biomechanical model



a) b)

Figure A: Biomechanical model of a backpack including: a) the loads from the backpack acting on the human and b) the shoulder reaction forces.

Appendix B: Biomechanical model inputs.

Table B.1: SCBA biomechanical model inputs for the twelve selected firefighters during the static representative posture for the initial hose pick-up phase of the high-rise pack lift and carry task. The x and z components of the SCBA weight are relative to the coordinate system defined by the horizontal and vertical components of the SCBA, as shown in Figure 1.

	Model inputs											
Participant Number	SCBA Mass (kg)	SCBA Weight (N)			SCBA angle (degress)	Relative Upper Strap Angle (degrees)	Relative Shoulder Reaction Force Angle (degrees)	Horizontal Distance from SCBA Centre of Mass to Shoulder Centre (m)	Distance from SCBA Centre of Mass to Back (m)	Vertical Distance from SCBA Centre of Mass to Shoulder Centre (m)	Horizontal Distance from SCBA Centre of Mass to Shoulder Centre (m)
	m	W	Wx	Wz	β	θ1	α	a1	a2	d1	d2
S27	17.5	171.7	148.7	85.8	60.0	38.0	39.1	0.1901	0.047	0.2687	0.1691
S28	17.5	171.7	121.4	121.4	45.0	38.0	39.1	0.1901	0.047	0.2687	0.1691
S30	17.5	171.7	127.6	114.9	48.0	38.0	39.1	0.1901	0.047	0.2687	0.1691
S37	17.5	171.7	167.9	35.7	78.0	38.0	39.1	0.1901	0.047	0.2687	0.1691
S38	17.5	171.7	139.8	99.6	54.5	38.0	39.1	0.1901	0.047	0.2687	0.1691
S42	17.5	171.7	163.3	53.1	72.0	38.0	39.1	0.1901	0.047	0.2687	0.1691
S05	17.5	171.7	121.4	121.4	45.0	38.0	39.1	0.1901	0.047	0.2687	0.1691
S11	17.5	171.7	167.9	-35.7	102.0	38.0	39.1	0.1901	0.047	0.2687	0.1691
S19	17.5	171.7	121.4	121.4	45.0	38.0	39.1	0.1901	0.047	0.2687	0.1691
S32	17.5	171.7	170.7	17.9	84.0	38.0	39.1	0.1901	0.047	0.2687	0.1691
S34	17.5	171.7	131.7	110.1	50.1	38.0	39.1	0.1901	0.047	0.2687	0.1691
S47	17.5	171.7	127.6	114.9	48.0	38.0	39.1	0.1901	0.047	0.2687	0.1691

Table B.2: SCBA biomechanical model outputs for the twelve selected firefighters during the static representative posture for the initial hose pick-up phase of the high-rise pack lift and carry task. The x and z components of the lumbar and shoulder reaction forces are relative to the coordinate system defined by the horizontal and vertical components of the SCBA, as shown in Figure 1.

	Model Outpus							Acceptability Limits	
Participant Number	Lumbar Reaction Force (N)			Lumbar Reaction Force Angle (θ_2)	Shoulder Reaction Force (N)			Lumbar Reaction Lift Force (N)	Shoulder Reaction Force (N)
	L	Lx	Lz	Angle	S	Sx	Sz	Lz	S
S27	185.9	174.0	65.3	20.6	32.6	25.3	20.6	125.0	290.0
S28	182.3	157.2	92.3	30.4	46.2	35.8	29.1	125.0	290.0
S30	183.6	161.5	87.4	28.4	43.7	33.9	27.5	125.0	290.0
S37	180.5	178.5	27.1	8.6	13.6	10.5	8.6	125.0	290.0
S38	185.4	169.2	75.8	24.1	37.9	29.4	23.9	125.0	290.0
S42	183.4	178.9	40.3	12.7	20.2	15.7	12.7	125.0	290.0
S05	182.3	157.2	92.3	30.4	46.2	35.8	29.1	125.0	290.0
S11	159.7	157.4	-27.1	-9.8	-13.6	-10.5	-8.6	125.0	290.0
S19	182.3	157.2	92.3	30.4	46.2	35.8	29.1	125.0	290.0
S32	176.6	176.0	13.6	4.4	6.8	5.3	4.3	125.0	290.0
S34	184.3	164.2	83.7	27.0	41.9	32.5	26.4	125.0	290.0
S47	183.6	161.5	87.4	28.4	43.7	33.9	27.5	125.0	290.0

Appendix C: Microsoft Kinect® for Windows

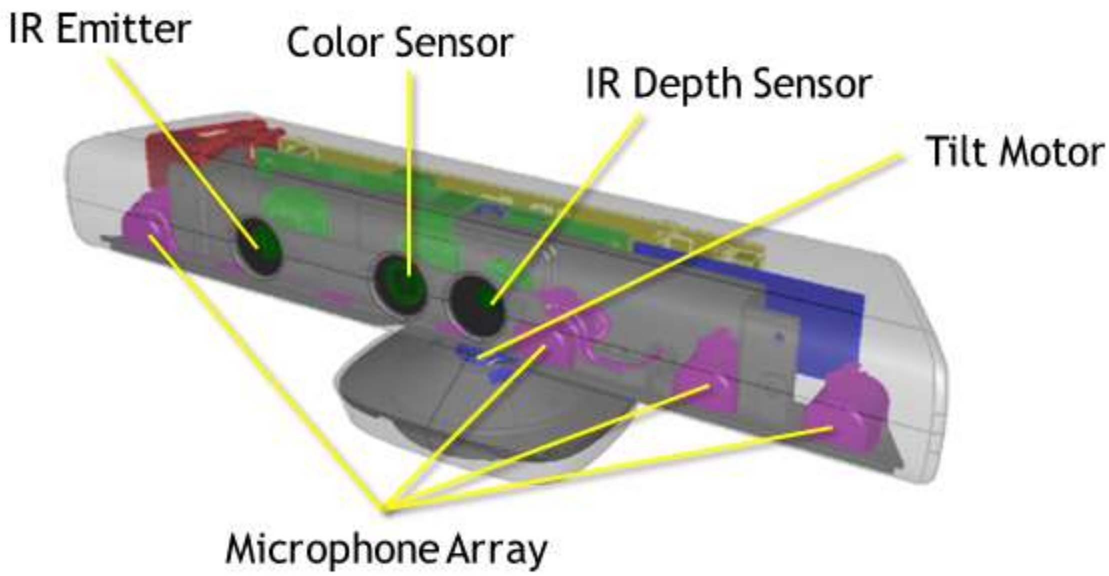


Figure C.1: Sensor components of the Microsoft Kinect® for Windows v1 showing including the colour and depth data sensors (from https://msdn.microsoft.com/en-us/library/jj131033.aspx).

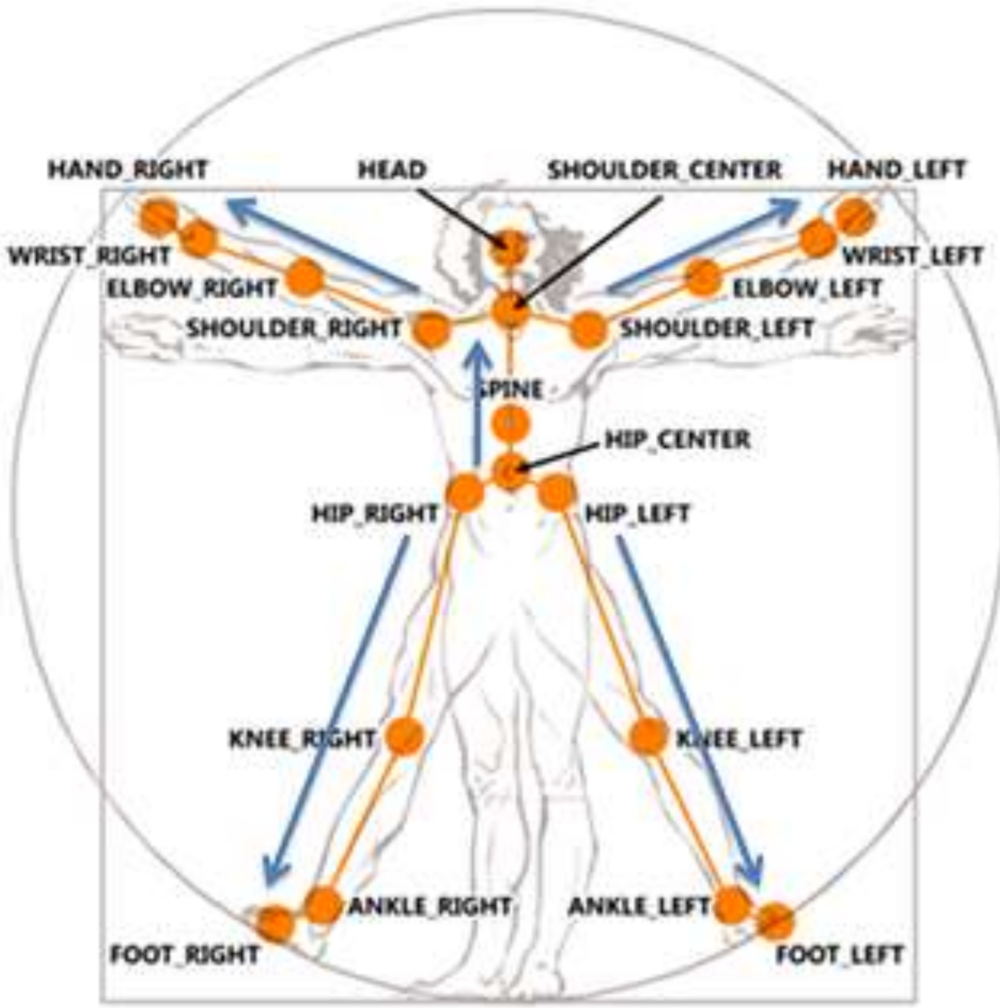


Figure C.2: Diagram showing the joints tracked by the skeletal tracking function within the Microsoft Kinect® for Windows (from: https://msdn.microsoft.com/en-us/library/jj131025.aspx)

CHAPTER 5: GENERAL DISCUSSION

1. Overview

Digital human modeling (DHM) technology was first developed in the late 1960's, and has had a substantial positive impact on workplace ergonomics over the last several decades (Don B. Chaffin, 2008). However, improvements to this technology are still needed to ensure that it can be used as accurately as possible (Chaffin, 2008). The body of work presented within this thesis contributes both to improving virtual ergonomics technology as well as to broadening the scope of the traditional application of this technology from manufacturing environments to firefighting tasks. Indeed, the ergonomic assessment of firefighting tasks presents unique challenges, which may be best overcome by using DHM technologies.

DHM tools have been developed and used within the context of three main industries: automotive, aerospace, and military (Chaffin, 2008). Within these three industries, DHM tools have been used to assess factors including vehicle interior and plane cockpit design, workstation design, and manufacturing ergonomics. Other industries have adopted these technologies as they become more affordable and their benefits are more widely understood. However, there are still many more industries that have yet to benefit from these technologies. Firefighting is an occupation that has under-utilized DHM technologies but could benefit greatly from their usage due to the complexity of the biomechanical modeling required to account for personal protective equipment as well as the challenges and dangers associated with using traditional observational methods for ergonomic analyses of firefighting tasks.

DHM simulations can be conducted by manually manipulating the digital human model, driving the digital human model using motion capture data, or relying on posture prediction algorithms to estimate the most appropriate postures and movements for the digital human model given a set of task constraints (Stephens & Godin, 2006). These simulations can either be done for the assessment of current ergonomic issues using actual worker anthropometrics, or to assess hypothetical or future scenarios (i.e. proactive ergonomics) using general population-based anthropometric dimensions such as small (5^{th} percentile), average (50^{th} percentile) and large (95^{th} percentile) humans. The posture prediction method is perceived as the ideal method for DHM technology given its perceived ease of use and limited requirement for resources. However, posture prediction is a complicated and evolving science that, depending on the model used, is reliant on a thorough understanding of human performance from both a cognitive and biomechanical perspective (Chaffin, 2008). Despite the accomplishments to-date in developing cognitive and biomechanical models for integration in DHM software, there is still more research needed to ensure that these models are valid across a broad range of applications and the associated task constraints.

Given the current limitations of the posture prediction method, the research studies presented in this dissertation focus on posturing digital human models through manual manipulation or by driving their movements using motion capture data. First, posturing guidelines for digital human manual manipulation, were evaluated during a breadth of automotive manufacturing tasks (Chapter 2). Next, we applied an ergonomic action assessment tool to identify the presence of musculoskeletal injury risks in firefighters during common fire suppression tasks, which is an understudied population in the field of occupational biomechanics relative to their high injury reports (Chapter 3). Finally, DHM software and load carriage biomechanical modeling principles were used to conduct a more in-depth analysis of the musculoskeletal injury risks associated with a high-injury risk firefighting task (Chapter 4). Overall, the research presented within this dissertation contributes both to automotive and firefighter industry-specific ergonomics knowledge as well as to the broader evolving area of virtual ergonomics.

2. Summary of Dissertation Research Main Findings

This dissertation consists of three distinct yet complimentary studies that highlight the evolution of the virtual ergonomic tools from the traditional application in the automotive manufacturing sector to a more unique application in firefighter ergonomics. The benefits of this research extend beyond the simple assessment of musculoskeletal injury risks for these two workforces to include a general contribution to the state of the art of virtual ergonomics tools.

2.1 DHM manual manipulation posturing guidelines

Traditional methods for ergonomists who employ manual manipulation to posture digital human models within a virtual environment for subsequent ergonomic assessment rely on few, if any, instructions for ergonomists with respect to posturing strategies. Commonly, ergonomists performing these assessments are expected to have a general understanding of human movement and behaviour. However, as identified by Potvin et al. (2008) and McInnes et al. (2009), these ergonomists may benefit from posturing guidelines to assist with estimating real worker postures. These guidelines include: 1) limiting neck extension, 2) maximizing proximity to the object, except during overhead tasks, 3) minimizing trunk and shoulder rotations, 4) being mindful of the installation effort, and 5) maintaining visibility with the part. Study 1 shows that the use of these posture guidelines by experienced ergonomists while performing simulations of six car and six truck assembly line workstation simulations resulted in more accurate postures and more conservative estimates of injury risk when compared to simulations performed without specifically adhering to these guidelines (Chapter 2). Furthermore, the study also confirmed the importance of digital human model anthropometry whereby simulation accuracy is greater when the digital human model is scaled to the height of the real worker.

The implications for these findings are two-fold: 1) posturing guidelines that encourage the consideration of motor behaviour strategies by real workers should be considered when simulating workstation tasks without a visual representation of how a worker actually performs the task, as often happens in proactive ergonomics, and 2) where possible, digital human models should be scaled using accurate anthropometrics or, when feasible, multiple simulations should be performed using digital human models that have been scaled to a wide range of heights.

2.2 Posture evaluation of firefighters during fire suppression tasks

In Chapter 3, ergonomic assessments using a manual version of the Ovako Working Posture Analysing System (OWAS, Karhu et al., 1977) were conducted on 48 firefighters performing three different simulated fire suppression tasks: 1) hose pull, 2) hose drag, 3) high-rise pack lift and carry. Pre-recorded 3D video using the Microsoft Kinect® was used to identify the postures for assessment at critical phases of each task (e.g. hose initial contact, ambulation preparation, ambulation, and hose pull). The task phase identified as being in most need of ergonomic action was picking the hose up off the floor, particularly for the high-rise pack lift and carry task. Some of the postures contributing to the high OWAS action classification scores include adopting postures with bent and twisted trunks as well as squatting on two bent legs or kneeling. Overall, the variability in strategies used did not allow for the consistent identification of trends based on firefighter demographics or anthropometrics, which suggests an individualized approach to injury prevention may be needed (Chaffin, 2008). As a result, further in-depth analysis of the tasks and postures is needed to identify individualized modifiable factors to help reduce the risk of injury to firefighters as they perform these common fire suppression tasks.

2.3 Considerations and implementation of virtual ergonomics for firefighters

An in-depth analysis of the initial hose contact phase of the high-rise pack lift and carry tasks from Chapter 3 was conducted in Chapter 4 using two DHM tools, 3DSSPP and Jack. The purpose of using the DHM approach was three-fold: 1) DHM tools offer a suite of sophisticated ergonomic tools for ergonomic assessment of current tasks as well as for task modifications, 2) the motion capture data collected could be streamed into one of the DHM software programs for potentially expedited simulations, and 3) inclusion of some of the external loads (i.e. bunker gear and the self-contained breathing apparatus (SCBA)) not accounted for in using the manual OWAS method (Study 2). Previous research on 2D load carriage biomechanical models (e.g.; (Bryant et al., 2000; Kim, 2014; Pelot et al., 2000) was used to estimate the shoulder and lumbar reaction forces based on assumptions concerning the interface between the SCBA and the firefighter, the design and inertial properties of the SCBA, and firefighter dimensions. Although the proposed model offered reasonable shoulder and lumbar reaction force outputs given the load of the SCBA and the firefighter postures studied, the results are expected to be under-representative of the actual external loads. The limitations in using free-body diagrams for the implementation of biomechanical models in DHM software are discussed, as are recommendations for the future. Nonetheless, the study findings highlight the importance of accounting for external loads within the DHM software, including the weight due to the bunker gear and the external loads caused by the SCBA. Additional loads, including those caused by the helmet and boots shoulder also be included in the future.

Comparisons between DHM software and the selected ergonomic outputs highlight the value in accounting for external loads caused by personal protective equipment, but also emphasize the need to ensure that DHM simulations are as accurate as possible so that erroneous postures do not impact the ergonomic output. While Jack likely has more accurate posturing capabilities, including the ability to stream Microsoft Kinect® motion capture data, it cannot account for the external loads acting on the human other than at the hands. 3DSSPP has more primitive posturing capabilities, which may contribute to more erroneous simulations; however, this software does allow for the input of external loads over several regions on the digital human model including the shoulder and lumbar regions. The strengths and limitations of each of these software programs are discussed in greater detail in Chapter 4. From a practical perspective, all the ergonomic tools studied highlight a need for changes to the strategies used by the firefighters during the initial hose contact phase of the high-rise pack lift and carry task and/or to the tasks itself. Proactive assessments of this task using DHM software may be useful in suggesting task modifications.

3. Limitations

Multiple DHM software exists on the market, each with their own strengths and weaknesses (Chaffin, 2008). Only two of these, Jack and 3DSSPP, were selected for usage and evaluation in the current dissertation. The rationale for the selection of these tools was based on: 1) ease of integration of the results within the existing stakeholder ergonomic protocols (e.g. Ford Motor Company, Chapter 2), 2) tool availability, and 3) tool familiarity. These tools are also widely used in the field of ergonomics, making the relevance of this research applicable within the broad ergonomics community. However, our failure to use other or additional DHM software is a limitation of this research. For instance, both AnyBody Modeling System (Anybody Technology A/S, Aalborg, Denmark) and Santos (SantosHuman Inc., Coralville, IA, USA) claim to have the ability to model external loads including backpacks (Anybody and Santos) and personal protective equipment (Santos). However, Anybody is more complex than both Jack and 3DSSPP as it requires users to build whole-body models from libraries of musculoskeletal structures. Santos uses posture prediction methods that are based on optimization criteria to simulate tasks. These posture prediction algorithms have not been tested with the firefighter population and may not be valid given, for example, the magnitude and distribution of external mass from the personal protective equipment (Frost et al., 2015; Park et al., 2015; Park et al., 2010; Rosengren et al., 2014) and the cognitive and physical demands placed on the firefighters (Bos et al. 2007). Thus, while there are alternative DHM software tools, Jack and 3DSSPP DHM were deemed to be the most appropriate for this dissertation.

One benefit to using the Jack DHM software was the ability to posture the digital human models using both Microsoft Kinect® motion capture data and manual manipulation. Ideally, only the Microsoft Kinect® data would have been used to posture the digital human models; however, this method proved to be insufficient on its own. Thus, the hybrid approach to running the digital human model simulations allowed for obvious errors in skeletal tracking to be easily corrected. Errors in skeletal tracking may be caused by the presence of the bunker gear since it distorts the anatomical outline of the firefighters that is expected by the skeletal tracking algorithm embedded within the Microsoft Kinect® software development kit. This distortion may cause incorrect assignment of the virtual skeletal segments to the subject. Thus, a validation of the skeletal tracking abilities of the Microsoft Kinect that considers bulky clothing, such as bunker gear, is needed prior to developing a DHM simulation protocol that looks to increase its dependency on Microsoft Kinect® motion capture data streaming. In fact, such a validation should be performed regardless of the motion capture technology being used.

The studies presented in Chapters 3 and 4 served to identify the risk associated with performing selected fire suppression tasks. While we were successful in doing this, the next step in our research will be to develop solutions that reduce the identified injury risks across all observed fire suppression tasks. As proposed in Chapter 4, the use of DHM technology with field-friendly motion capture technology such as the Microsoft Kinect® may aide in this goal. Nonetheless, two limitations of this body of work are that we have not yet sought the input of the end-users for developing solutions nor have we proposed an intervention study. However, in adhering to the knowledge translation framework proposed by Sinden and MacDermid (2014), we plan to share our research with the end-users and engage them in next steps.

4. Implications of Research Findings

This research has implications that span the interests of software developers and occupational biomechanists, as well as the end-users in automotive manufacturing and firefighter ergonomics. While, there is a large body of evidence supporting the benefits of using DHM software for workstation design both within and beyond the automotive manufacturing sector (Chaffin, 2005; Chaffin, 2008; Chaffin, 2007; Colombo et al., 2013;

Stephens & Godin, 2006), the technology is still evolving and improvements, such as those suggested in this dissertation, are needed.

In particular, the posturing guidelines described in Chapter 2 should be considered in DHM software posture prediction algorithms, or be embedded as posturing constraints or reminder tools during manual manipulation of the digital human models. Additionally, Jack software developers should consider: 1) improving the Microsoft Kinect® data collection and streaming process to drive Jack digital human models and 2) developing a module that allows for the inclusion of external loads on the digital human model at locations other than the hands. The software currently has the ability to import CAD objects, assign inertial properties to those objects, and then fix those objects to the digital human model. However, these objects are currently not included in the biomechanical models that are used during the ergonomic assessment processes within Jack. Embedding the ability to account for these external loads would allow Jack to be more broadly used, particularly with workers who wear heavy personal protective equipment, such as firefighters. Chapter 4 describes a simplified approach to modeling the external loads caused by the SCBA and may be useful to potential software engineers who may decide to address this need within Jack.

Jack and 3DSSPP DHM software are typically either used to assess the worker safety in current workstations or to identify potential injury risks in future workstations early in the product design stage (Colombo et al., 2013). However, Jack's ability to drive digital human models with motion capture data lends itself to being a potential ergonomic training tool whereby almost immediate postural feedback can be provided to the worker.

As reviewed by Williams-Bell et al. (2014), there have been efforts to develop serious games and virtual simulation tools for firefighter training; however, these tools have yet to consider the physical demands on the firefighters from an ergonomics perspective. With the above recommendations for DHM software improvements for better Microsoft Kinect® data streaming and the inclusion of external loads, Jack may be a viable tool for quick, inexpensive, and easy-to-use postural training for firefighters in field-like environments such as firefighter training facilities. Alternatively, serious gaming software developers may also be able to incorporate ergonomic modules into their software.

Virtual ergonomics tools are undeniably helpful in identifying injury risks to workers (Colombo & Cugini, 2005). Furthermore, as highlighted in a report by the U.S. National Research Council on human performance (Baron et al., 1990), an additional benefit of DHM software is its ability to aide in the communication of human performance capabilities and attributes to stakeholders charged with considering ergonomic issues in the workplace (Chaffin, 2008). Thus, while Chapters 3 and 4 identify firefighter injury risks, it is ultimately the responsibility of the employers, health and safety teams, policy makers, ergonomists, supervisors, and the workers themselves to make the necessary changes to ensure that injury risks are avoided once identified (Chaffin, 2008). The research presented within this dissertation is expected to help these stakeholders make informed decisions and develop or refine programs related to injury prevention during fire suppression tasks.

5. Future Directions

The body of work presented within this dissertation demonstrates the evolution of virtual ergonomics tools both with respect to methodological improvements for the software as well as applications to new industries. An important weakness in the current suite of DHM software is the limited opportunity to account for important external loads caused by personal protective equipment. Research presented in Chapter 4 described simplified ways of accounting for external loads caused by the bunker gear and the SCBA; however, more work is needed to account for external loads caused by equipment including the helmet and boots.

The Microsoft Kinect® has many benefits related to field-based 3D motion capture data collection for ergonomic applications; however, this dissertation also highlights many of the weaknesses involved in using this tool. Determining improved methods for using this inexpensive, portable, and easy-to-use motion capture device is a future goal. Preliminary research from the Toronto Rehabilitation Institute proposes a marker-based approach using the Microsoft Kinect® to reduce missing data due to body occlusion (Parahoo, 2016). We will also examine the performance of the second generation of the Microsoft Kinect® system.

Finally, an important next step in this program of research is to discuss the development of ergonomic training programs with both the Hamilton Firefighters Association as well as other firefighter associations across Canada. By involving the end-users in the knowledge translation plan (Sinden and MacDermid, 2014), we hope to develop effective next steps for the successful implementation of this research. A proposed idea for research implementation is to pair the Jack DHM software and the Microsoft Kinect® for the development of a cost-effective, easy-to-use, and enjoyable virtual training program. This training program could assist paid, volunteer, and/or firefighters-in-training with learning and adopting proper movement mechanics during fire suppression tasks by providing postural feedback with respect to musculoskeletal injury risks. Indeed, research suggests that occupationally relevant movement-guided training approaches may be a successful method of reducing injury risk in firefighters (Frost et al., 2015). Furthermore, simulation-based virtual training, at least in the context of healthcare professional education, has also been shown to be effective at improving knowledge, skills and behaviours (D. A. Cook et al., 2011), particularly when feedback is provided (C. H. Shea & Wolf, 1999). As proposed by Williams et al. (2014), we expect the development of this virtual simulation training program for firefighter injury prevention to be beneficial; however, engaging with the end-users to refine and develop this idea is an important first step.

6. Conclusions

The benefits of virtual ergonomics technologies are significant, yet improvements are still needed for this technology to be more useful and reach a broader spectrum of workforces. Nonetheless, these technologies allow for a relatively easy in-depth analysis of workplace postures using a breadth of ergonomic tools. A novel contribution of this research is that it transposes well established and widely used ergonomic tools from the automotive manufacturing industry into the realm of firefighter injury prevention. In doing so, areas for improvement to virtual ergonomics technologies are proposed, particularly with respect to accounting for external loads caused by personal protective equipment.

An equally important outcome of this research is the identification of posture-related injury risk factors to firefighters during fire suppression tasks. Although there are multiple reports of injury statistics, there is limited literature that focuses on firefighter movement mechanics as it relates to musculoskeletal injury risks during fire suppression tasks. The inclusion of external loads caused by the bunker gear and SCBA is a novel contribution to this area of research; however, continued efforts are needed to accurately estimate the external loads caused by the complete set of personal protective equipment including the helmet and boots. Nonetheless, this research represents important first steps in assessing firefighter ergonomics using virtual ergonomics technologies.

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