# DETERMINANTS OF OCCUPATIONAL HEALTH IN FIREFIGHTING

# IDENTIFYING DETERMINANTS OF FIREFIGHTER WORK HEALTH AND TASK PERFORMANCE: IMPLICATIONS FOR INJURY MANAGEMENT

By

KATHRYN E. SINDEN BSc., MSc., R.Kin.

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AUTHOR: Kathryn E. Sinden BSc.(Kin) (University of Waterloo), MSc.(Kin.) (University of Waterloo), R.Kin.

SUPERVISOR: Joy C. MacDermid PT, Ph.D.

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## Abstract

**Introduction:** Applied occupational health research is complex and requires transparent communication between stakeholders to facilitate development and implementation of injury management strategies. Firefighting as a physically demanding, male-dominant occupation provides a unique context to develop and implement injury management strategies.

**Thesis Objectives:** To investigate how individuals perform occupational tasks within a physically demanding occupational context considering the interrelationship between personal, task and environmental factors. A secondary objective was to evaluate the research partnership as integrated knowledge translation using the Knowledge-to-Action (KTA) Framework.

**Methods**. A qualitative study was used to identify barriers and facilitators experienced by female firefighters. Dartfish movement analysis software was adapted to analyze kinematics associated with firefighter tasks. Relative and absolute reliability was used to establish measurement properties of Dartfish methods. Regression models identified the relative importance of individual factors on firefighter task performance. A case study of the research partnership using knowledge translation (KT) theory identified critical phases in developing occupational health research partnerships.

**Results**. The qualitative study identified sex/gender and task/environment effects on firefighter task performance and injury risk. Tracking positional co-ordinate data using Dartfish demonstrated excellent relative reliability ($ICC_{2,1}$ = 0.84-0.99) and lowest absolute reliability (SEM = 0.01m-0.11m). Strength was the strongest independent predictor of firefighter task performance time where increasing strength was associated with faster time. The case study identified components of the KTA Action Cycle that supported and described collaborative occupational health research.

**Conclusions**. Although female firefighters share commonalities with their male counterparts, unique personal attributes and social experiences affect how they experience firefighting. Dartfish provides a reliable tool to measure kinematics in an applied context. Although refinements are required, recommendations for data collection and extraction using Dartfish in occupational contexts are provided. Occupational health research imbedded in KTA cycle confirms the importance of partnership with stakeholders to ensure the feasibility and relevance of the research.

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This dissertation is dedicated to my father, David R. Sinden (1948–2011); your strength and courage were inspiring - thank you for always believing in mine.

## Preface

The following details author contributions to each of the papers included in this dissertation.

Chapter 2: A Qualitative Study on the Experiences of Female Firefighters

Authors: Kathryn E. Sinden, Dr. Joy C. MacDermid, Stephanie Buckman, Bonnie Davis, Tracy Matthews and Carrie Viola

Kathryn Sinden conducted secondary data extraction and analysis, interpreted study findings and manuscript preparation. Dr. Joy MacDermid developed the study design, facilitated interpretation of the study findings and provided assistance with manuscript preparation. Stephanie Buckman, Bonnie Davis, Tracy Matthews and Carrie Viola contributed to study design, conducted the study and conducted an initial data analysis.

Chapter 3: Developing a measurement strategy to assess occupational body mechanics: Identifying lower extremity postures during a field-controlled firefighting lift task

Authors: Kathryn E. Sinden, Dr. Joy C. MacDermid, Dr. Thomas R. Jenkyn, Dr. Sandra Moll

and

Chapter 4: Reliability of a video-motion analysis system to identify upper extremity postures and head movement during performance of a field-controlled firefighting lift task.

Authors: Kathryn E. Sinden, Dr. Joy C. MacDermid, Dr. Thomas R. Jenkyn, Dr. Sandra Moll

Kathryn Sinden developed the research questions, provided the study design, prepared ethics submissions, collected the data, analyzed the data, interpreted the data, and drafted the manuscripts. Dr. Joy MacDermid reviewed ethics submission, refined the research questions and study design, interpreted study findings and provided editorial assistance with manuscript preparation. Dr. Tom Jenkyn consulted on data collection procedures and analysis. Dr. Sandra Moll contributed to study design and provided editorial assistance on manuscript preparation.

<u>Chapter 5: Individual attributes, cardiovascular measures and strength as predictors of firefighters' task performance</u>

Authors: Kathryn E. Sinden, Dr. Joy C. MacDermid, Robert D'Amico, Karen Roche

Kathryn Sinden developed the research question, contributed to the study design, aided ethics submissions, collected the data, analyzed the data, interpreted the data, and drafted the manuscript. Dr. Joy MacDermid prepared the ethics submission, refined the research questions and study design, interpreted study findings and provided editorial assistance with the manuscript. Robert D'Amico and Karen Roche facilitated data collection and will contribute contextual editorial assistance with the manuscript.

Chapter 6: The Evolution of FIRE-WELL: Improving Firefighters' Health through Research and Partnership

Authors: Kathryn Sinden and Dr. Joy MacDermid

Kathryn Sinden and Dr. Joy MacDermid collaborated on developing the research question, study design and content. Kathryn Sinden drafted the manuscript and Dr. Joy MacDermid provided editorial assistance on the overall manuscript and content particularly with respect to theoretical model development.

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# Chapter One: Introduction

Work associated with paid employment contributes to individuals' self-identity, provides an environment for developing social networks and affords opportunities for intellectual growth. Subsequently, the loss of work due to injury or illness can profoundly impact individuals' social and physical functioning, individual-family role and responsibilities, and individuals' relations with their employer[1,2]. Although occupational health research is positioned to develop evidence-based interventions towards mitigating workplace injury, the effectiveness of these interventions on disability outcomes remains inconclusive[3–5]. Using theoretical frameworks to guide occupational health research while developing contextually relevant strategies, may address methodological gaps and improve research outcomes. This dissertation advances our understanding of firefighter work health and task performance in an occupational context and uses knowledge translation theory to frame the research partnership with a local fire service, which made the research possible.

## Occupational Health Research: Preventing Work Injuries

Occupational health research identifies factors that predispose workers to injury and determines effective interventions towards mitigating consequences of workplace injury. The following section reviews the burden associated with occupational injuries; the effectiveness of strategies to prevent workplace injuries; and the complexity involved in stakeholder interactions that facilitate development and implementation of these strategies.

*Burden of Occupational Injuries*.

The burden associated with workplace injuries is well documented[6,7]. Analysis of data collected from the 2003 Canadian Community Health Survey[6] identified 630 000 (3.8%) Canadians experienced at least one activity limiting occupational injury in 2003. Overexertion or strenuous movement was the most commonly reported mechanism of injury (25.4%) and sprains or strains was the most commonly reported injury type (39.8%); the hand (28%) and low back (16%) were the most commonly reported injured body regions[6]. Similar findings were reported by the Ontario workers' compensation board (WSIB) where 43% of injuries resulting in lost time were reported as sprains and strains and 19% were the result of overexertion; in contrast to the national injury characteristics, the low back (20%) was the most commonly reported body region injured[7].

The cause of workplace injuries is multifactorial and hence theoretical models are often used to describe the complex relationships between factors such as physical demands associated with task design (i.e., tool design, equipment), organizational work factors, individual attributes and general population health morbidity factors as prognostic factors related to workplace injuries[8–11]. Disparity between these domains and individual capacity can impose an increased risk of injury to the individual[11]. An area of focus in work injury prevention research is developing injury intervention strategies that address these factors in combination and / or in isolation towards mitigating injury risk.

*Injury Prevention Strategies*

There is mixed evidence that injury prevention strategies designed to mitigate workplace injury have been effective. Several recent Cochrane Reviews[3–5] have analyzed the effectiveness of non-pharmacologic interventions on work disability outcomes (i.e., sick leave, injury frequency, pain) and have found no consistent beneficial effects on mitigating workplace injury. For example, within the construction industry, interventions were considered across five domains: the worker/work team (including worker capabilities and actions as causative factors of injuries); the worksite; materials; equipment including design and maintenance; and work organization[5]. Regulatory actions, safety campaigns, training, and inspections were implemented to mitigate workplace injury yet only company oriented, targeted safety campaign interventions resulted in moderate, long term effects on reducing injury rates[5].

A second review sought to identify the effects of ergonomic design and training programs (i.e., ergonomic equipment, supplementary breaks, ergonomic training and combined training/equipment and patient lifting interventions) on work injury outcomes specifically related to arm, neck and shoulder complaints[3]. Moderate quality evidence was found to support that arm rests with an alternate mouse (i.e., 'ergonomic' mouse) was effective in reducing neck and shoulder disorders although limitations included heterogeneity within the existing literature and a noted paucity of research directed towards determining the effectiveness of ergonomic interventions on upper extremity work-related disorders.

Interestingly, case studies appear to demonstrate more convincing effects of injury prevention strategies on work disability outcomes. For example, two studies[12,13] evaluated the effectiveness of ergonomic interventions, in reducing soft tissue injury symptoms and improving posture. Fabrizio et al.[13] evaluated the effect of administrative and behavioural intervention on self-reported pain measures in a female office worker. Administrative modifications included adjustment to chair metrics (i.e., seat height, seat pan dimensions, arm rests) and behavioural modifications included educational information about postural adjustments and work pace. Although improvements in self-reported pain were observed compared to baseline, the effects of the intervention were likely confounded by the ongoing physiotherapy treatment sought by the participant. Furthermore, details of the intervention methodology were not clearly documented consequently it was difficult to ascertain which component of the intervention impacted the outcome. Methodological documentation is often weak in occupational health research particularly with respect to details of the intervention. This makes extrapolating findings to additional occupational contexts challenging and compromises gaining insights into understanding the mechanistic impact of critical components of the intervention on injury and work function.

Although single-case interventions as documented in the case study literature demonstrated effectiveness on work health outcomes[12,13], this approach rarely occurs in practice. Comprehensive approaches designed to affect the entire workforce are preferred and are more commonly implemented. For example, De Weese et al.[14] studied the effects of a multi-phase approach on work health in a manufacturing environment. A designated individual was responsible for implementing and monitoring a two-phase intervention: phase one was administered in year one and involved completion of objective job descriptions (i.e., physical demands analyses), elimination of workplace stressors and development of a daily stretching program. Phase two was implemented over the subsequent two years (years two and three) and involved identification of minimum strength requirements and task specific post-offer, pre-employment screens. The intervention resulted in a decrease in the total number of recorded injuries, decrease in the accident reporting rate and an associated decrease in employee turnover.

In addition to single-case and comprehensive approaches to injury prevention, participatory ergonomics (PE) supports a multi-level, systems approach to injury prevention. PE engages workers in development of injury prevention strategies through empowering collective discussions and using informed decision-making with respect to work-task and organization modifications[15]. Haukka et al.[16] conducted a randomized control study to identify the effectiveness of a PE intervention in reducing musculoskeletal disorders in kitchen workers. The results identified no effects of the intervention on number of sick days or time loss between the intervention and control groups[16]. Using a process evaluation[17] to determine the effective and non-effective components of the intervention may have proven useful to understand the operating mechanisms within the intervention. Cole et al.[18] undertook implementing PE interventions across four different occupational contexts and also found low impact on reducing workplace injuries (specifically musculoskeletal disorders); a process evaluation approach was used to reflect on the barriers and facilitators to implementation. The primary barriers associated with implementing the PE intervention were related to stakeholder involvement including daily production pressures, securing employee time, management involvement and stakeholder frustration with delays involved in the research process[18]. The complexity associated with research implementation of workplace interventions is succinctly captured in this study and supports the need for a robust theoretical framework to support and understand the relationship between key constructs in PE interventions[18] and occupational health research.

In summary, although systematic reviews of non-pharmacologic interventions fail to identify an overwhelming effect of work injury prevention strategies on work health outcomes[3–5], individual studies identified a positive effect of contextually specific, multi-dimensional approaches to preventing work injuries[12–14]. The ability to coordinate multiple stakeholders (i.e., employers, union members, insurers, workers and researchers) in the development and implementation of injury management strategies is a unique challenge faced in occupational health research that may also impact the effectiveness of the intervention strategies[18,19]. Utilizing theoretical frameworks to guide occupational health research is anticipated to inform processes required to effectively engage multiple stakeholders in the research process which is further anticipated to facilitate contextualized, effective work injury prevention interventions. In response to calls for increased utilization of theory in occupational health research, theoretical frameworks drawn from knowledge translation research have been increasingly utilized to facilitate collaborative-based occupational research[20–24].

**Knowledge Translation (KT) in Occupational Health Research**

Multiple terms are used describe the process of translating knowledge into practice. For example, implementation science is commonly used in European research contexts; diffusion and knowledge transfer are terms used to describe this process in the United States; knowledge transfer and exchange (KTE) is the terminology used in some Canadian research contexts[25]. The Canadian Institutes of Health Research (CIHR) uses the term knowledge translation (KT) and defines KT as "a dynamic and iterative process that includes the synthesis, dissemination, exchange and ethically sound application of knowledge to improve health, provide more effective health services and products and strengthens the healthcare system"[25,26] . This definition of KT supports that transferring knowledge into practice is an active process requiring collaboration of all stakeholders in the uptake of knowledge and associated change in practice or behaviour. The Knowledge-to-Action (KTA) framework[25–27] is a theoretical reflection of the constructs included in CIHR's definition of knowledge translation and was selected to inform this thesis research.

The KTA Framework was selected to inform this thesis research for several reasons including: (i) the assumption that successful implementation of knowledge requires iterative collaborations and discussions between the knowledge users and the knowledge creators (ii) the allowance for integration of knowledge from a breadth of knowledge sources (iii) the fluidity between knowledge creation and knowledge implementation through the action cycle[25,26,28]. Furthermore, previous research has demonstrated success using the KTA framework in occupational health research in developing a tool for use in developing injury management strategies[23].

The KTA framework is based on assimilation of multiple theories of behaviour change and planned action and is comprised of two processes: (i) Knowledge Creation and (ii) the Action Cycle[25–27]. The Knowledge Creation funnel represents the process of filtering and synthesizing knowledge towards a specific application or tool. The Action Cycle is a cyclical phasic process representing an iterative process of tailoring knowledge for implementation in response to contextual demands. The phases of the Action Cycle include: (i) problem identification in response to knowledge selection and review (ii) adapting knowledge to a specific context (iii) identifying barriers to knowledge use (iv) selecting, tailoring, implementing interventions (v) monitoring knowledge use (vi) evaluating identified outcomes (vii) sustaining knowledge use. Although these components are depicted as discrete and sequential, a primary assumption of the KTA framework is the processes within the Action Cycle between the Action Cycle and Knowledge Creation are fluid and dynamic suggesting flexibility to the model during application.

The KTA framework provides a useful, iterative process for collaborative occupational health research. For example, the process of distilling knowledge with respect to current injury prevention strategies, and evaluating the feasibility of developing and implementing research outcomes with respect to the goals of the fire service were seen as a necessary initial steps in building the research partnership. The dynamic relationship between Knowledge Creation and the Action Cycle of the KTA, particularly evident when "adapting knowledge to local context" and "assessing barriers to knowledge use"[23], was anticipated to provide critical guidance in developing and strengthening the research partnership while maintaining the overarching research objective. The overarching objective of the research partnership is to develop an evidence-based injury management program in response to the injury burden associated with firefighting.

### Injury Burden and Occupational Demands of Firefighting

Our communities' safety is largely dependent on the services provided by firefighters. Firefighters perform high-hazard, physically demanding tasks while being exposed to environmental factors that contribute to prevalence of injury and disease[29–32]. Furthermore, the non-cyclical, physical demands associated with firefighting impose significant burden on firefighters' cardiovascular and musculoskeletal system. In a recent report by the Ontario workers' compensation board (WSIB), police officers and firefighters accounted for the largest portion of allowed lost time claims (11%)[7] and soft tissues injuries due to overexertion were the most frequent reported injury type and mechanism[7,30,33,34].

*Physical Demands Associated with Firefighting*.

Tasks associated with firefighting such as heavy lifting and unsafe work postures[32,34] in addition to awkward postures and body motion[29,35] have been associated with higher injury rates amongst firefighters. Although the link between biophysical attributes related to these job factors and injury rates is not clear, one study identified the high physical load associated with firefighting tasks predisposed firefighters to higher risk of injury[30].

In response to the physical demands associated with firefighting, the relationship between individual strength and firefighter tasks has been a recent focus in the literature[36–39]. For example, strength training tasks such as bench press and sprinting ability have been correlated with faster performance time during various firefighter tasks[36]. These results suggest that specific training protocols may be effective at improving task performance however, the link between improving task performance through strength and the impact on injury rates is not clear. Further longitudinal research is required to determine the effects of specific muscle strength training on firefighting work health and injury.

In addition to muscle strength when fighting a structural fire, firefighters typically work at 60-100% of their cardiovascular capacity, imparting a significant load on the cardiovascular system[40,41]. A recent systematic review[42] identified the functional demands associated with firefighting are compounded as there is a prevalence of population-based risk factors (i.e., hypertension, diabetes mellitus, obesity, smoking) for cardiovascular disease in the fire service suggesting the need for wellness programs in firefighting. Although evidence suggests benefits of wellness promotion programs on firefighter health outcomes such as reductions in obesity and smoking, improved cardiovascular performance and higher job satisfaction[43,44] there are no enforced training requirements or health promotion initiatives in firefighting. Furthermore, while firefighters participating in wellness programs experienced overall health benefits, these findings did not extend to their work health as they were slightly more likely to report a workers' compensation injury[44]. These findings suggest that interventions designed to affect overall health may not apply to improvements in firefighter work health. It may be the physical demands and complex work context associated with firefighting may influence the effects of wellness programs on firefighter work health. For example, the impact of multi-dimensional factors affecting firefighter work health, is evident in an epidemiological study that identified relationships between workplace injuries, personality constructs and individual attributes including marital status, years of service, age and gender[31].

*Gender and Firefighting*.

In addition to managing the physical demands associated with firefighting, female firefighters continue to represent a minority in the fire service[45], providing a valuable context to identify the way in which sex/gender constructs intersect with work health. Liao et al.[31] studied the correlates between individual attributes and injury characteristics amongst firefighters and identified that female firefighters report 33% higher injury rates than their male counterparts. Furthermore, physiological differences between males and females have been identified during simulated firefighting tasks[46–48] further supporting that sex/gender constructs are important considerations in firefighter health research. Seeking to understand how female firefighters as a gender minority experience the work environment was anticipated to provide valuable insights into how the context of firefighting impacts firefighting task performance and ultimately, their work health.

In summary, research positioned to identify the interrelationship between individual attributes, strength, cardiovascular parameters and firefighter task performance is needed in the development of a comprehensive injury management program that also addresses individual training needs, improving the efficacy of firefighter injury prevention programs. However, assessing task performance and postures associated with firefighting is challenging. Firefighters perform complex tasks, in physically and environmentally stressful situations. Furthermore, task performance variability between workers and between shifts contributes to challenges in quantifying task mechanics particularly in dynamic, non-cyclical work such as firefighting. Another important variable to consider when developing task analysis approaches for applied occupational research is the expertise of the individual who will be using the task assessment method and applying the results[49]. Although multiple methods exist for assessing biomechanical exposures in occupational contexts[49], developing a method that is accessible for implementation and interpretation by the firefighters was a critical consideration in the development of tools designed to assess constructs of firefighter task performance.

**Occupational Task Observation Techniques**

A recent systematic review of observational methods used for task analysis at work[49] identified thirty different observational methods. Variability in applying the different observational methods (i.e., general versus upper extremity work versus manual handling varied) was noted as well as their overall utility amongst stakeholders (i.e., researchers, occupational health/safety practitioners/ergonomists and workers/supervisors). Expanding on this research, surveys of practicing ergonomists in Canada[50] and the United States[51] identified the most common observational methods were those used to identify injury risk associated with manual material handling (i.e., NIOSH lifting equation[52], Snook lifting tolerance tables[53], Biomechanical Models). The normative standards inherent in these analyses represent a potential limitation of these approaches. Comparisons to normative data may not capture societal changes in constructs impacting the standards (i.e., strength, cardiovascular tolerance) or individual variability, both important considerations for clinicians when developing injury management strategies including return-to-work planning and pre-employment screens.

An additional limitation of the observational methods relates to the multiple computations required when utilizing these methods (i.e., NIOSH lifting equation[52]), requiring a certain level of expertise and training. Subsequently there is limited uptake of these approaches by individuals responsible for implementing health and safety in occupational contexts[50]. Health and safety personnel are often workers assigned responsibility for health and safety in their work contexts which involves implementing strategies falling under the health and safety mandate of the company including: conducting task-based analyses; facilitating return-to-work planning; and developing injury management programs in response to health and safety policy. Therefore, accessibility and feasibility are necessary for task-based observational methods to be used when evaluating or implementing injury prevention strategies.

In contrast to ergonomists, health and safety personnel frequently use ergonomic assessments and physical demands analyses (PDAs) to capture physical demands associated with job tasks[50]. Ergonomic checklists and PDAs are supported by standard guidelines[54] and provide critical information used by employers and health and safety personnel when developing injury prevention strategies and during return-to-work planning. PDAs provide an objective baseline tool of task requirements used for comparative analysis to establish the gap between individuals' functional capacity and job requirements[54,55]. Although this comparison does not provide a general, calculated risk assessment, measurement of the differential is used to develop criteria and content for individualized training programs aimed to improve task performance and ultimately reduce risk of injury. Furthermore, there is support that individualized training programs are more effective towards injury prevention and health promotion amongst firefighters than more generalized approaches[56,57].

When developing individualized training programs, in addition to PDAs, information regarding posture including range of motion, strength and mobility is used determine individuals' functional ability to perform job tasks. This information is often obtained from clinical assessments however clinicians' evaluation of body postures is usually subjective[58]. Although quantitative methods are available (i.e., OptiTrack, Vicon, Qualisys©) they are not readily accessible to clinicians due to costs, requirement of specialized training and complex data processing[58]. Developing approaches to measure task-based postures that demonstrate strong measurement properties while providing utility for individuals across various contexts (i.e., academics, ergonomists, joint health and safety committees, clinicians) would address the gap between recommended, evidence-based tools, the approaches used by health and safety professionals[50,51] and clinicians[58].

One approach to reduce the gap between stakeholders is to identify tools preferred by ergonomists that could be readily scaled to use by clinicians and health and safety personnel. Basic tools commonly used by ergonomists to evaluate work-task postures include tape measures, stopwatches, digital cameras and video cameras[51]. Developing an evidence-based approach that leverages these preferred tools while supporting less complex computational methods, may bridge the gap between evidence and practice in physical ergonomics and injury management. For example, using movement analysis software that uses inputs from video cameras, may be one approach that bridges this evidence-to-practice gap.

*Dartfish*

Dartfish is one example of movement analysis software ideally suited to motion analysis in occupational and clinical contexts. The software enables analysis of video inputs from a variety of sources and provides kinematic outputs to facilitate spatial and temporal analysis of postures associated with task-based assessments. Although Dartfish was originally developed to facilitate athletic training its utility has been expanded to research applications assessing patient outcomes pre- and post-treatment of shoulder impairment[59] and assessment of complex movements associated with functional tasks[60–65]. Dartfish was selected for the postural research conducted in this dissertation as it has been proven reliable when identifying upper and lower body movements associated with complex tasks conducted in laboratory settings[59,61–64] and during athletic task performance[60].

A commonly cited feature of Dartfish is that it provides an accessible platform to assess kinematics associated with functional tasks using video-based inputs. Furthermore, the software can be utilized by individuals with varied experience[64] and the analysis can be completed and interpreted with ease. However, a primary limitation with Dartfish is the analysis is limited to two-dimensional outputs, which presents a challenge for considering use in occupational contexts where movements are multi-planar and transverse across non-linear space. Developing methods that address this limitation is necessary prior to expanding application of Dartfish to movement analysis applications in occupational contexts. Furthermore, for the data from Dartfish to be useful in applied occupational health research, identifying its measurement properties including the reproducibility, accuracy, feasibility and effects on clinical decisions and outcomes is necessary[66]. Consequently, a primary purpose of the research studies conducted using Dartfish was to determine the reproducibility of this software when identifying upper and lower body postures associated with a field-controlled, firefighting task. Furthermore, the outcomes from this research are intended to identify methods that could be used to assess task-based postures in occupational contexts.

**Statement of Research Problem**

Occupational health research has made important contributions towards understanding factors that predispose individuals to injury and to developing strategies to mitigate workplace injury. However, the effectiveness of these interventions remains uncertain[4,5]. Variability in occupational context and the complexity of multiple stakeholders in occupational health research may be contributing to these inconclusive findings. Using theoretical frameworks from knowledge translation may improve research methodology and intervention effectiveness.

Furthermore, although evidence suggests that occupational injuries in Ontario, Canada are declining, firefighting remains a physically demanding occupation that continues to contribute to the majority of workplace injuries[7]. Consideration of individual attributes is important as developing individualized injury management programs are likely to be more effective than generalized programs. Furthermore, developing reliable methods to evaluate the effectiveness of these interventions is important to enable additional contextual applications.

Consequently, the overall objective of this dissertation was to consider the individual within the larger context of firefighting through analysis of individual attributes and firefighting task performance. The research was guided by principals of integrated knowledge translation informed by the Knowledge-to-Action Framework[25–27].

**Composition of Dissertation Papers**

The dissertation is compromised of four papers (Chapters 2-5) and a chapter from a CIHR Institute of Musculoskeletal Health and Arthritis / Canadian Arthritis Network Casebook (thesis Chapter 6) highlighting the impact and value of research conducted in musculoskeletal health. The papers include a qualitative paper and three research studies that were completed as part of the candidate's PhD program requirements in the School of Rehabilitation Sciences at McMaster University.

The qualitative study (Chapter 2) provides foundational insights into the unique barriers and facilitators to working as a female firefighter and highlights some of the challenges that women experience working in a male-dominant occupation. A critical finding was that female firefighters feel a need to focus on strength training as a means to demonstrate independence during physically demanding aspects of firefighting. Although physical demands associated with firefighting contribute to higher rates of injury amongst male and female firefighters, less is known about the mechanics associated with firefighter task performance. Two manuscripts (Chapters 3 & 4) describe the development and reliability of a method designed to measure kinematics during firefighting task performance. Methods were developed on male and female firefighters to facilitate translational application across gender in future research. Chapter 5 used regression modelling to identify the impact of individual attributes, strength and cardiovascular parameters on firefighter task performance time during a hose drag task. The models developed from this research are anticipated to inform future research directed to identify the impact of injury prevention interventions on work disability outcomes. A final manuscript (Chapter 6) provides an overview of the process and key components required in developing and sustaining the firefighter research partnership positioned to identify and develop an evidence-based injury management program. Two manuscripts have been published (one in a peer-review journal and the other peer-reviewed for publication in a CIHR Casebook). The remaining three manuscripts are being submitted to peer-reviewed journals for publication consideration. Permission to reproduce the manuscripts is stated in the appropriate chapter.

In summary, the studies and research in this dissertation seek to explore the relationship between the individual and firefighter task performance within the context of injury management and to use knowledge translation theory to guide the research and overarching research partnership with the fire service.

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## Chapter Two

**Title: A Qualitative Study on the Experiences of Female Firefighters**

Authors: Kathryn E. Sinden, Joy C. MacDermid, Stephanie Buckman, Bonnie Davis, Tracy Matthews and Carrie Viola

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**Abstract.**

*Purpose:* Firefighters are exposed to high physical and psychological occupational factors while providing an essential service to our communities. Female firefighters represent a minority group in this male dominated occupation. The purpose of this study was to qualitatively determine the impact of a male dominated, physically demanding occupation on women's work health and job satisfaction through the experiences of female firefighters.

*Methods:* A phenomenological approach was used to collect data through semi-structured, recorded interviews with female firefighters. The recorded interviews were transcribed into text and inductive thematic analysis was used to qualitatively analyze the transcripts.

*Results:* Review and analysis of the participant responses identified seven themes: physical demands / difficulties, gender related physiological differences, compensatory strategies, equipment mal-adaptation, earning respect, negative attitudes of male counterparts: impact on social inclusion and health behaviors, recognition of injury risk.

*Conclusion:* Female firefighters are exposed to increased risk of injury due to the psychological and physical occupational stressors in firefighting. Implications of this

research are provided and include recommendations for future research to target the physical and psychosocial aspects of firefighting.

Keywords: Musculoskeletal Disorders; Injury Prevention; Phenomenology

## 1. Introduction

Firefighters provide urgent and essential services to our communities. Meeting the requirements of their role requires intermittent periods of peak physical activity placing them at increased risk for musculoskeletal and cardiovascular injury compared to other occupations [1-3]. Occupational risk factors contribute to onset of musculoskeletal injury and include the force, repetition, duration, work postures and contact stress involved in work tasks [4,5]. Psychosocial work demands and individual psychological stress have also been identified to pre-dispose workers to musculoskeletal injury and adverse health status [6]. Workplace injury prevention programs have demonstrated effectiveness in mitigating workplace risk factors and reducing the burden associated with workplace disability in firefighters [7]. Understanding the factors that predispose firefighters to injury at work with a view to risk reduction is critical to development of effective injury prevention programs.

In addition to recognition as a physically demanding occupation with psychosocial factors, firefighting is identified as a male dominated work environment. A male dominant work environment has been classified as one where over 60% of the employees are men [8]. Women have recently entered the occupation of firefighting and represent just over 3% of firefighters in the United States [9]. Despite the small number of female firefighters, understanding the relationship between occupation and gender for firefighters of this early cohort is essential when developing effective injury management programs. Previous research [2,3] has examined the epidemiology of firefighting. For example, Liao et al. (2001) [2] explored correlates between firefighter injury frequency and

duration, demographics, personality and economics to facilitate development of strategies to mitigate injury. An important finding was that female firefighters reported 33% more injuries than their male counterparts, a relationship that persisted when age, race, tenure and personality were controlled. Additionally, previous researchers have examined the effect of gender on both simulated firefighting task performance [10,11] and physiological outcomes [12,13]. Females' cardio-pulmonary, muscle strength, muscle endurance and task performance outcome measures consistently differed when compared to their male-counterparts. Another study designed to determine the affect of ergonomic modifications on firefighting task performance identified that females respond differently than males on occupational
performance [14]. These studies suggest that gender is an important factor to consider in epidemiology related to firefighting as well as firefighting task performance.

Female firefighters offer a unique cohort to understand the barriers and facilitators to performing work in a complex work environment. As women respond to the physical and physiological demands of firefighting differently than men, it is reasonable to anticipate that they will also experience the work environment differently than their male counterparts. The interrelationship between gender, physical demands and psychosocial constructs in firefighting has not been extensively explored. A study that explored the risk of musculoskeletal injury associated with two firefighting tasks interviewed the female firefighter participants to obtain information about the perceptual difference in risk in firefighting between males and females [15]. The results of the interview were not presented but might have provided useful information about adaptive strategies that may have further informed the ergonomic analysis. Understanding how women experience the work environment and identification of barriers and facilitators to work performance may inform how these job factors interrelate. Furthermore, the interrelationship between gender and job content may assist in identification of potential occupational risk factors and facilitate development of an effective injury management program. Consequently, the aim of this study was to understand how a male-dominant, physically demanding work environment impacts female work health and job satisfaction through exploration of the positive and negative experiences of female firefighters.

## 2. Methods

### *2.1 Design*

A phenomenological approach is used in qualitative research to describe individuals' experiences with a particular phenomenon and to determine the meaning of that experience for the individuals [16]. Descriptive phenomenology requires that the researcher be aware of any pre-existing ideas or suppositions about the phenomena and bracket these biases to allow objective analysis of the phenomenon [16]. Interpretive phenomenology does not require bracketing as the premise is that biases cannot be separated from the researcher and consequently, cannot be put aside [16]. The primary purpose of this study was to understand the lived experience of women working in a male-dominant, physically demanding occupation consequently a descriptive phenomenological approach was used to collect and analyze qualitative data.

*2.2 Participants and Recruitment*

The occupational context for this study was a firefighting service in Southwestern Ontario. A recruitment letter was forwarded to all five female firefighters who were employed in this municipality, which resulted in a response rate of 80%. The study participants consisted of 4 female firefighters who had a mean age of 35.2 years and 3.7 years of firefighting experience. All participants had a college education.

*2.3 Data Collection*

To identify the barriers and facilitators experienced by female firefighters, semi-structured telephone interviews were conducted and recorded for purpose of analysis. Telephone interviewing has been identified as a reliable and efficient method of obtaining individual experiences when compared to face-to-face interviews [17,18]. Furthermore, telephone interviewing was anticipated to limit participants' response inhibition. Four independent researchers conducted the interviews, which lasted approximately 45 minutes, to ensure confidentiality of participant responses. The interview questions were investigator developed to elicit discussion regarding the experience of female firefighters and included questions regarding: job expectations and attitudes, workplace injuries and recommendations for the employer, treatment provider and peers contemplating firefighting as an occupation (see Figure 2.1). The interviews were conducted while the participants were off-shift to create an environment that would facilitate direct and honest responses.

Prior to the qualitative interviews, a brief questionnaire was provided to each of the study participants to obtain demographic information, employment history, physical fitness and work injury information that might impact their experiences as a firefighter. As well, descriptive phenomenology requires that researchers become aware of any pre-suppositions or bias related to the phenomenon and use methods to separate prior experiences from the data collection and analysis [16]. Each of the researchers in this study identified and bracketed their experiences and bias related to firefighting and female experience in a male-dominated occupation to limit interpretative biases prior to conducting the interviews. A post-positivist approach framed the data collection and analysis [19].

*2.4 Analysis*

The recorded interviews were transcribed into type written text and qualitatively analyzed using an inductive thematic analysis approach [20]. Inductive thematic analysis is a method for identifying, analyzing and reporting patterns or themes independently from existing theoretical frameworks or categories. The analysis followed the six phases of thematic analysis described by Braun and Clarke (2006) [20]; familiarizing with data, generating initial codes, searching for themes, reviewing themes, defining and naming themes, and producing the report.

The transcribed interviews were initially reviewed by one of the researchers and highlighted prevalent statements, ideas and contemplations. Common perceptions and experiences were identified and developed into themes. All of the researchers met to discuss the identified themes and any bracketed assumptions or biases. The reviewer returned to the transcripts to modify and refine the identified themes subsequent to discussion with the researchers. For each theme, the reviewer then assigned text for coding and identified quotes associated with the codes from the transcripts. The researchers again reviewed the coding from the transcripts and quotes and any differences were discussed until group consensus was reached. To verify the trustworthiness of the data, the identified themes and quotes were also reviewed with the study participants ("member checking"). Feedback was requested including identification of themes that may be missing and those that represented their intended expressions of experience as a female firefighter. Any identified differences were again discussed amongst the researchers until general consensus was obtained.

## 3. Results

Commonality between participants was acknowledged in their passion and desire to help people, which were further identified as the primary reason for entering the firefighting profession. Based on review and analysis of the participant responses, seven themes were identified. All study participants provided agreement to the identified themes. A description of each of the identified themes is provided below followed by quotes that reflect perspectives associated with the identified themes.

### *Physical Demands / Difficulties*

It was clear from the interviews that the participants recognized that firefighting is a physically demanding profession. Various components of firefighting were discussed as being the most physically challenging including "…advance the hose line up several flights of stairs…" and "...another physically demanding part of the job is after the fire is out is doing overhaul. You're pulling down ceilings, pulling down walls like demolition…". The participants all discussed that their initial expectations of firefighting were that the job would be both physically and mentally demanding but the physical element represented a potential barrier to entering the profession.

> "The tests that we have to do to get on made it clear that it was going to be [physically] demanding because that was very, very difficult."
>
> "Mentally, I knew that I could do it (firefighting) but physically that was more what I was concerned about."

The participants also recognized the strength and endurance demands associated with firefighting and the importance of maintaining their physical fitness to maintain occupational performance.

> "…you have to have endurance, to be a firefighter…your adrenaline helps you get through…it helps you advance the hose line up and helps you to put the fire out but then after that the adrenaline is gone and you still have to take down the ceiling and the walls and break up the floors so you really need endurance."
>
> "(Firefighting) is a very physically demanding job and part of my responsibility was to maintain my physical abilities."

*Gender Related Physiological Differences*

There was recognition among the participants that physiological differences between males and females predispose females to disadvantages when performing firefighting tasks. The female firefighters also identified a commitment to maintain their level of physical ability to be able to perform to the occupational standards expected of firefighters.

> "…for a woman it is difficult because you are working above your head and our upper body strength is not the same as a mans because that is just the way we are built…"

> "Females are already 20% not as strong as their male counterparts…so you really have to maintain that or you're going to be weaker."

*Compensatory Strategies*

Participants discussed that the physiological disadvantages experienced compelled them to develop compensatory strategies to be able to perform their work tasks effectively. During the interviews, the female firefighters demonstrated creative, innovative solutions to mitigate deficits experienced with firefighting tasks. The female firefighters expressed that learning to perform tasks independently was an important consideration in being accepted as a member of the team.

> "Body mechanics more than anything…the guys can usually manhandle things; I had to learn to use my body a bit more effectively."

> “There’s these special plugs that don’t allow water in and are really hard to push together. I learned a trick of just putting them between my knees and as I push with my hands, I push with my knees at the same time. I can put them together now no problem.”

> “There can’t be anything we can’t do or else we’re never going to be accepted… in the fire department you have to learn to never ask for help… you have to figure out how and just find a way…just do it!”

*Equipment Mal-Adaptation*

Several participants acknowledged that critical elements of firefighting equipment were too large and better suited for their male counterparts. The participants discussed that they were able to develop and implement adaptive strategies to alleviate these barriers. According to the participants, equipment designed for women is commercially available but is not always locally provided.

> “The boots are always too big on me and the bunker pants…everything is just kind of big and fits more loosely because it’s suited more for a man. They do have female gear out there but we don’t have it.”

> "…we have a breathing apparatus that includes a face piece and the face piece was too big so I let them know and they got me a smaller one and that happened with three other girls as well…"

*Earning Respect*

Respect as a firefighter was discussed from various perspectives. A common theme identified was the need for rookie firefighters to earn their respect within the firefighting team. The participants discussed women entering the profession need to remove any preconceived ideas and thoughts that they will be accepted into firefighting because of their gender.

> "You have to earn your stripes basically, you know what I mean…their respect. A lot of women walk right on the job expecting their respect and you have to earn it…"

> " When you come on new, whether you are [male or female], you have to pay your dues…you have to prove yourself before you get some respect."

An additional perspective discussed by the participants was that firefighting is well respected by the public, which was viewed as a positive factor that contributed to rationale for entering the profession.

> "..the fact that it's a highly respected job with the public. The public, they trust you, the people are usually always glad to see you."

*Negative Attitudes of Male Counterparts: Impact on Social Inclusion and Health Behaviors*

The participants collectively commented on experiences where gender influenced behavior and attitudes of their male counterparts. The attitudes of male counterparts were discussed as both a barrier and a facilitator to a positive work environment, job performance and adopting adaptive strategies to reduce injury risk. Although the participants were prepared for the challenges and negative perceptions that they were exposed to upon entering firefighting, negative male attitudes towards female firefighters affected overall job satisfaction and work environment. Female firefighters discussed that there was some resistance from their male counterparts as they were excluded from training and social activities. Negative male attitudes also affected their ability to request assistance to perform physically demanding tasks and further the adoption and implementation of health and safety behaviors. When implementing strategies to overcome equipment maladaptation, female firefighters discussed that they were exposed to negative comments from their male counterparts. Interestingly, the participants tended to downplay this negative male behavior. Furthermore, the participants indicated that development of strategic health and safety programs specific to females would be counterproductive and be perceived negatively by their male counterparts. The participants acknowledged that attitudes towards female firefighters are changing and progressing in a positive direction. There was a sense that this progression would make the job more enjoyable and improve job satisfaction.

"Some people have attitudes that aren't going to change no matter what you do, no matter how good of a firefighter you are…you're a woman in man's job and you shouldn't be here."

"..They (male counterparts) refused to train us because they didn't want us to be good. Because if we were good, then I guess they wouldn't look masculine maybe, I don't know…..they wouldn't even let me play basketball with them because it was a 'boy's club'."

"…To ensure job satisfaction…maybe put them (female firefighters) in a station that you know that the guys there are going to welcome a female firefighter rather than think that she does not belong there."

"..it's not a really big deal what the gloves are. They don't really say anything, just "Oh…she needs her little gloves" kind of thing. Big deal."

"Now it's becoming more acceptable (females in firefighting). I don't think that the girls coming on would have as much of a hard time as I did – and I didn't have it that rough."

*Recognition of Injury Risk*

The participants identified that fire fighting is a physically demanding job and identified the physical strength and endurance requirements of firefighting increase of risk for injury. They further identified emotional and mental strains resulting from work conditions and acknowledged workplace programs that support and provide strategies to manage this aspect of their job. The participants discussed recommendations to reduce injury risk, which focused on changing biomechanical exposure and maintaining whole body conditioning to ensure effective job performance.

> "…I had to take a medical call where there was an infant death and that was kind of hard to deal with however, we do have a program within the fire department called 'Critical Incident Stress' and if there is a critical incident that would cause us stress…we have the people in the fire department…who are trained to come and talk with us."

> "I don't think that there's a difference because I'm a female…. Generally a lot of the time when you get injured it's the back because you're lifting the wrong way and you injure your back…you get a little bit out of shape so you don't do things properly."

**4. Discussion**

This study identified the occupational experiences of female firefighters with a view to inform health and injury prevention. While female firefighters share the same high task demands as their male counterparts, their physical differences, the fit of equipment and the social environment all contribute to increased task difficulty. Female firefighters expressed that these challenges were not unexpected and that they were prepared to develop strategies to ensure continued occupational and task performance.

One of the prevalent themes recognized by the participants was that firefighting is a physically demanding occupation. Successful firefighting performance has been positively correlated with muscular strength [11], aerobic [11-13] and anaerobic capacity [11,13]. Simulated firefighting tasks are used to quantify the strength and endurance requirements of firefighting. The hose pull, stair climb while carrying a hose pack, simulated victim drag and equipment hoist are firefighting tasks identified to represent the physical and physiological demands of firefighting [11]. These tasks are similar to the firefighting tasks that comprise the Candidate Physical Ability Test (CPAT) [12,13] a standard entry test that firefighters must complete and pass. Studies [11-13] have recently identified the high physical and physiological requirements associated with successful completion of the CPAT and have further recommended programs targeting aerobic and anaerobic fitness to improve firefighting performance. The participants in this study recognized the importance of maintaining their overall fitness to sustain their firefighting performance. It will be important in developing physical maintenance programs to consider both the physical demands of firefighting and physiological gender differences.

The experiences of female firefighters support previous research [12,13] that females perform less well than males on aerobic, anaerobic and strength outcomes during simulated firefighting tasks. Furthermore, females are much more likely to be unable to complete the firefighter CPAT due to fatigue than men with an 85% versus 9% failure rate across genders [12]. The majority of participants did not acknowledge endurance when discussing physiological differences between males and females. Participants may not separate strength and endurance concepts in a biomedical way or be aware of gender differences in endurance since they are not as visibly obvious as strength differences. The participants identified strength-training programs as a way to mitigate physical gender differences in firefighting and again, did not address strategies to compensate for endurance differences. The findings of this study suggest that female firefighters require increased awareness of the importance of maintaining strength as well as endurance to ensure optimum firefighting performance. Our study findings also suggest that the impact of gender on the endurance component of training programs is an important aspect to address in future research.

In addition to compensating for strength deficits the female firefighters in our study discussed development of compensatory strategies to ease performing challenging firefighting tasks. The primary adaptation strategy employed was using body momentum to facilitate task completion. Although the adaptive strategies facilitated task completion, there is an association between awkward postures and increased risk of musculoskeletal disorders (MSDs) that was not recognized by the participants [4,5]. Occupational risk factors that contribute to onset of musculoskeletal disorders and disability from work include the force, repetition, duration, work postures and contact stress involved in work tasks [4,5]. The adaptation of compensatory strategies may be a mechanism for female firefighters to prove their ability and worth to their male colleagues. Regardless, this reluctance to request assistance when performing tasks that exceed their physical capability is a potential contributor to injury risk to female firefighters. Future research to determine the biomechanical and physical burden associated with adaptive strategies used in firefighting is recommended to inform development of injury management programs. Gender is also recommended as an important consideration of this research.

In addition to developing adaptive strategies to facilitate performance, the female firefighters discussed that the fit of firefighting equipment challenged their occupational performance. Equipment fit has been commonly identified as an issue for women entering firefighting [9,21]. The participants specifically expressed that the face piece component of the self-contained breathing apparatus (SCBA) was too large and required modification. The fact that equipment is necessary but burdensome is a recurrent theme in firefighter health (1,22). The SCBA is a critical component of firefighting equipment as it protects firefighters from inhaling smoke, ash and other inhalants. Proper fit of the face piece is important to the health and safety of individuals working in occupations such as firefighting where there is exposure to inhalation hazards [23]. Females' facial anthropometric measures significantly differ from men as they have significantly smaller, shorter and narrower faces then men [23]. The study participants did discuss limitations with the equipment with their fire department and were able to obtain equipment that fit. That female firefighters clearly identify and articulate concerns with safety equipment but do not request assistance with difficult tasks, may suggest that there is a "safety threshold" for firefighters. If a work condition is considered life threatening it may be that it warrants discussion and action within the fire department compared to a work condition that is considered an injury risk. Regardless, the participants' negative experiences with equipment reflect study findings which support that protective equipment, especially the face piece component of the SCBA, needs to be adapted to the anthropometric measurements of the individual user.

Females perceive that they have to prove themselves to their male colleagues, as reflected in their creative and innovative solutions to challenging tasks and equipment mal-adaptation. The participants acknowledged that firefighting as a profession is highly respected by the community [24] respect within the profession however, was perceived as something to be earned. Earning respect was associated with performing less meaningful tasks, which may be a way of demonstrating ability and willingness to perform any job that contributes to the team success. Female firefighters demonstrate behaviors to ensure that they do not represent a burden and to gain the respect of their male counterparts.

Previous research [25] has found that females working in a male-dominated environment experience greater levels of anxiety and job strain, sexism, and lower job satisfaction and increased co-worker conflict. Psychosocial work demands and individual psychological stress have been also been identified to pre-dispose workers to musculoskeletal injury and adverse health status [6]. Furthermore, job satisfaction and health outcomes have been strongly and positively correlated to the amount of social support at work [8,25,26]. Our study also identified that job satisfaction would be improved by ensuring a positive work environment where female firefighters are placed into stations where women are accepted and integrated into the work environment.

Furthermore, discussions reflected negative experiences with being excluded from social activities participated in by the participants' male counterparts. Several of the participants were excluded from social activities and when invited, determined that the activities were not appropriate or they did not have the skills required to participate in the activities [i.e., golf]. Social exclusion as a construct of workplace psychosocial factors has been identified as a precursor to adverse health effects including predisposition to MSDs [6,8]. An opportunity for future research is to determine the impact of recreational and social exclusion on health outcomes including musculoskeletal disorders. Interestingly, the participants all discussed that despite these perceptions and experiences, there is a sense of growing acceptance and reduced stereotypes from their male counterparts.

The findings of this study suggest that female firefighters in this cohort are exposed to multiple gender specific factors that increase risk of injury and adverse health outcomes. Interestingly, 75% of the study participants did not perceive that females are at greater risk of injury. A possible explanation of this finding is that this study population has been exposed to prior negative male attitudes and is developing coping strategies to equalize with their male counterparts. Psychological and emotional stress has been identified as an important hazard of firefighting [1,21,24,27]. Our study participants identified exposure to emotionally stressful situations but they were not clearly identified as an injury risk factor. This may be because of stigma associated with mental health conditions [28].

A similar strategy was also noted when participants were asked about to provide recommendations specific for female firefighters to reduce injury risk. The respondents feared being isolated or singled-out by their male counterparts, as a common response was that males would perceive a female specific modification as "…something else we have to do for them." As firefighting is a "team-oriented" profession, it may be that these submissive coping strategies may be employed to maintain their status within the team and prevent isolation. A strategy where female firefighters minimize their individual needs to maintain safety and performance to gain respect from their male counterparts may be maladaptive in the longer term.

*4.1 Limitations*

Female firefighters represent a small but growing percentage of firefighters. The sample size for this study resembles the limited distribution of female firefighters in the profession. The 80% response rate does suggest that it is reasonable to expect that the responses are representative of the female firefighters in this geographical location.

Similar to other qualitative studies, the study findings and analysis are limited to our context, although the findings do extend support to larger-based research. For example, the study findings support literature that has identified occupational risk factors for female firefighters and the interrelationship between gender and psychosocial work factors.

The interview questions were developed to elicit personal insights into the lived experience of a female working in a physically demanding, male dominant work environment. Questions surrounding experiences with gender issues may have influenced their responses however the questions were developed to understand the general experience of female firefighters. The identified themes represent synthesis and analysis of all interview questions.

An important consideration for future research is the perception and experience of male firefighters with female firefighters. Our study was limited to experiences of female firefighters in a male dominated occupational environment. The experiences of male fire fighters would provide relevant information about their perceptions of barriers and facilitators of integrating female firefighters into firefighting and may further inform important considerations for development of occupational risk management programs.

*4.2 Implications*

Based on the results of this study, female firefighters in this municipality are exposed to multiple occupational factors [1,8] that increase risk for musculoskeletal disorders (MSDs) [6]. Future research directed towards extending these findings to other local municipalities should be considered as well as understanding male firefighter perspectives. These study findings do suggest that gender differences need to be considered in developing equipment, fitness maintenance programs and in social integration of a minority group into a gender dominated occupational environment. Preliminary recommendations include implementation of sensitivity training to facilitate integration of females in firefighting, developing comprehensive endurance and strength training programs and education regarding occupational risk factors for MSD.

## 5. Conclusions

The purpose of this study was to identify the female experience of working in a male dominant, physical demanding occupation. The context for this study was female firefighters in a Southwestern Ontario city. The findings lend support for previous research that demonstrates physiological differences between male and female firefighters. In addition, this study provides a unique perspective of the female emotional and physical stressors in a male-dominated occupational environment. The study findings suggest that female firefighters moderate their emotional and physical performance in a male-dominated environment to overcome negative male attitudes and pre-conceived notions of physical capability. Female firefighters are exposed to increased risk of injury due to the physical and emotional occupational stressors. Future research to mitigate injury should examine task components of firefighting and consider the interaction between gender and performance demands in firefighting tasks.

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## Manuscript Figures

**Figure 2.1 Example of Interview Questions**

- Why did you decide to become a firefighter?
- What expectations did you have when entering the firefighting profession about the demands of the job?
- Has firefighting met all of the your expectations? Why or why not?
- Have you experienced any discrimination, harassment or poor attitudes from your male counterparts?
- Have you experienced any problems with equipment you use for your job?
- Have you had to make any types of modifications to your environment in terms of equipment or attitudes of other people to maximize your abilities?
- What types of injuries are all firefighters likely to encounter and is there a difference because you are a female?
- What recommendations would you make to an employer in terms of safety and job satisfaction for a female firefighter?
- What recommendations would you make to females interested in becoming a firefighter and to prepare for this job?

## Chapter Three

**Title: Developing a measurement strategy to assess occupational body mechanics: Identifying lower extremity postures during a field-controlled firefighting lift task**

Authors: Kathryn E. Sinden, Joy C. MacDermid, Thomas R. Jenkyn, and Sandra Moll

This paper is being submitted to *Applied Ergonomics* for review and publication consideration.

**Abstract.**
Ergonomists use a variety of assessment tools to determine the biomechanical demands associated with occupational work tasks. A primary tool used by ergonomists is the video camera. Dartfish movement analysis software may provide a viable method to analyze kinematics associated with job task performance using video-based inputs. Our study identified the relative and absolute reliability of Dartfish for assessing lower extremity postures during a firefighting lift task, using video-based inputs. A sample of active, fit-for-duty firefighters was videotaped performing a firefighting lift task using a high-rise pack. Three data extraction methods available in Dartfish were utilized: angle tracking, positional co-ordinate tracking and single frame analysis. Video was obtained from cameras positioned in frontal and sagittal perspectives. Intra-class correlation coefficients ($ICC_{2,1}$), standard error of measurement (SEM) and minimal detectable change ($MDC_{90}$) were calculated for each data extraction method, for each camera position, for knee and hip movements. Excellent relative reliability was identified for extracting knee angle kinematics from the frontal ($ICC_{2,1}$ = 0.85 - 0.97) and sagittal camera ($ICC_{2,1}$ = 0.94 – 0.94) perspectives. Relative reliability for hip kinematics extracted from the frontal camera was excellent ($ICC_{2,1}$ = 0.84 – 0.97) for positional tracking and single frame extraction and substantial when using the angle tracking method ($ICC_{2,1}$ = 0.72).

Conversely, relative reliability for hip kinematics extracted from the sagittal camera perspective was excellent ($ICC_{2,1}$ = 0.81-0.98) for angle and positional tracking extraction and substantial ($ICC_{2,1}$ = 0.78) using single frame data extraction. Absolute reliability was lower for knee kinematics then hip kinematics from both camera perspectives. Overall, Dartfish supports a reliable platform to analyze lower extremity postures during a field-controlled firefighting lift task.

## 1. Introduction

Ergonomists use multiple tools and assessment approaches to determine the mechanistic interaction between workers and tasks performed in the workplace, however challenges have been identified with these methods including lack of a "gold standard"[1]. Furthermore, several operational limitations have been associated with the existing methods including: the technical requirements requiring high levels of movement analysis expertise; limited utility when assessing duration and frequency of work-tasks; limited integration of data particularly during assessment of bi-manual or multi-segmented tasks, and inability of the user to identify task adaptation strategies[1]. The identified limitations and challenges with these existing observational methods are critical concerns as we consider empirically based methods to integrate ergonomics practice and research. Ideally, the empirical methods used in laboratory-based ergonomic research should have both findings and methods that translate to real-world applications. This translational component is needed to ensure utility by those individuals using these tools towards improving the efficacy of safe-work recommendations and worker health (i.e., ergonomists).

As an example, a representative sample of 308 ergonomists practicing in the United States[2] identified a variety of assessment tools used when conducting ergonomic / work task assessments. Tools were classified into basic tools (i.e., tape measures, stopwatches, video, photos); observational methods (i.e., the Posture, Activity, Tool and Handling-PATH[3], Rapid Upper Limb Assessment-RULA[4]); direct measurement tools; and software. The most common tools used by ergonomists were tape measures (95.8%), video camera (96.1%) and stopwatches (88.3%); the most common injury-risk assessment was the NIOSH lifting equation (83%)[5]. Less than 20% of ergonomists reported using other work-task observational methods such as the REBA-Rapid Entire Body Assessment[6], the OWAS-Ovako Working Posture Analysis System[7] or the PATH[3], all common methods used by researchers to capture components of work task performance[1]. Similarly, a Canadian study of ergonomists and joint health and safety committees (JHSC) determined that ergonomists' preference towards using Snook maximum acceptable weight tables[8] and NIOSH lifting equations[5] to identify work injury risk was contrary to methods used by Joint Health and Safety Committees (JHSCs) who used work injury reports, ergonomic checklists and physical demands analyses[9]. The operational challenges perceived by JHSC when implementing more computational methods (i.e., NIOSH[5], Snook tables[8]) were provided as rationale for these differences[9]. Consequently, a precise, accessible assessment method of determining work injury risk factors that incorporates perspectives and preferences of all users (i.e., researchers, ergonomists and JHSCs) may facilitate translation between ergonomic science and ergonomic practice and improve work health outcomes.

Furthermore, existing observational methods to assess work task and injury risk are insufficient when tasks vary beyond manual material handling tasks which is often the reference task for the more frequently used methods[10] (i.e., NIOSH lifting equation[5] and Snook Tables[8]). The criterion for these methods may also not be applicable as findings from a recent study analyzing predictors of movement quality in firefighters suggest that evaluations of movements may need to be reflective of specific task demands to capture postures associated with unrestrained work tasks[11]. Methods for assessing key parameters associated with task performance must be measurable at the task level and the data collected must be practical and able to describe task performance parameters with precision[10]. However, accessible methods for assessing unrestrained task performance and work postures in applied occupational contexts are lacking[10,12].

One possible solution is using Dartfish (Lausanne, Switzerland), two-dimensional movement analysis software that enables kinematic analysis of video images and postures associated with task performance. Although the resulting outputs do not relate specifically to quantifying injury risk, they could be used to facilitate ergonomists' post-site analysis, provide inputs for observational assessments and identify individual, task-based postures providing important information about functional load. Because the software uses video-based inputs (i.e., audio video interleave files), data can be obtained from tasks performed in a variety of contexts. Dartfish has been found to measure reliable angles of movement during lower body movements including lifting tasks[13–15] however these methods and findings have been limited to laboratory settings that do not replicate complex occupational tasks and environments. Although not required when using Dartfish software, most laboratory studies using Dartfish have used skin-based markers in an attempt to improve data reliability and validity and have limited data extraction to single plane movements. A primary limitation of this approach for occupational research and ergonomic applications is that many workers wear personal protective equipment (PPE) and / or clothing, to provide a protective barrier between themselves and the work environment. Furthermore, assessing individuals in their occupational context introduces variability and complexity in task performance. Reliable measures of task performance that are possible in laboratory settings therefore may be more difficult to replicate in applied research contexts. Prior to using Dartfish in occupational contexts and for ergonomic applications, a methodological approach to extract reliable outcomes without the level of instrumentation and control utilized in laboratory-based research needs to be established.

Previous research[13–19] using Dartfish has focussed on identifying kinematics using the angle-tracking feature, which involves tracking an angle generated by connecting the skin-based markers, through a range of motion associated with a performed task. Although this data extraction method provides useful clinical data, it is limited to extracting angle data in two dimensions; therefore reliability of analyzing movements that move through the transverse plane may be compromised. Extending this approach to field–based applications requires identification of measurement properties using protocols more aligned with observing and assessing movement in occupational settings. Dartfish supports multiple analysis approaches through the analyzer module, enabling angle extraction from a single plane, tracking angles over time and tracking x,y positional co-ordinates over time. Developing methods to extract data using Dartfish that are both reliable and valid particularly when assessing movements that move in and out of single planes of movement is an important pre-requisite in creating a suitable option for ergonomic-based research and practice.

The current study uses a spectrum of Dartfish analytics to identify lower body kinematics associated with a field-controlled firefighting lift task with active duty firefighters wearing full PPE. Firefighters perform complex tasks in physically and environmentally stressful situations. Furthermore, task variability between firefighters and even between shifts contributes to the challenge in quantifying task mechanics in an applied occupational setting like firefighting. Establishing a reliable measurement approach to extract kinematic outcomes using Dartfish in a firefighting context offers the opportunity to understand the mechanics of firefighting tasks, which has not been extensively explored. Furthermore, the implications for developing a biomechanical measurement approach using simple, video-based inputs, an established preferred tool of practicing ergonomists, has implications for bridging the gap between laboratory-based occupational research, applied occupational research and ergonomic practice. Consequently, the current study proposed to identify measurement properties associated with Dartfish to identify lower body kinematics associated with performing a firefighting task.

The primary study objectives were: 1) to examine the intra-rater reliability of three Dartfish data extraction methods and two camera perspectives for assessing lower extremity postures during a firefighting lift task and 2.) to determine the minimal detectable change (MDC) and the standard error of the measurement (SEM) of Dartfish to improve the potential application of this approach in ergonomic practice.

**2. Methods**

2.1 Design

This study used intra-rater reliability between two data extraction times, using three data extraction methods (tracking angle, tracking positional coordinates and single frame analysis) to identify the reliability of Dartfish when extracting lower extremity movements during a firefighting task (Appendix A).

2.2 Participants

Firefighters (n=12) who held fully active, fit-for-duty status within in a single fire service in Southwestern, Ontario (n=471) represented the context for this study. A purposeful sample of female firefighters (n=6) and a random sample of male firefighter participants (n=6) were recruited (see Table 3.1). Prior to data collection, all firefighter participants provided written consent following review of the study purpose and data collection procedures. Ethics approval was obtained through the Hamilton Integrated Research Ethics Board (HIREB) (Appendix B).

<< Insert Table 3.1 about here >>

2.3 Procedures

*Context.*

All study protocols (Appendix C) were conducted in the firefighter's training facility. The training facility accommodates four (4) fire trucks, provides access to bona fide firefighting equipment and supports facilities that enable implementation of field-controlled firefighting task protocols.

*Task: Lifting a High Rise Pack (HRP).*

Lifting a HRP was selected for this reliability analysis because this group of firefighters identified this as a critical task in their job performance and one that is associated with higher injury rates. A HRP (19.5 kg.) consists of two lengths of firefighting hose (15 m each; 30 m total) including an attached nozzle and tools (i.e., wrench, couplings and other equipment). The HRP is used by firefighters when responding to structural fires (i.e., large warehouses, high rise) that contain hose cabinets and / or stand pipe systems. The HRP is lifted and carried from the truck to locations within a structure. Consequently, functional components associated with this task include lifting, carrying, walking and climbing stairs. Lifting the HRP from floor level and walking were the functional elements focussed on during this study. Furthermore, this task was selected as previous studies[13,15] identifying reliability of lower extremity postures using Dartfish have focussed on a lift task.

*Data Acquisition.*

Two digital video cameras (JVC HD Everio GZ-VX700, Full HD, AVCHD) were positioned on individual tripods; one facing participants in the sagittal plane and one facing participants in the frontal plane. The sagittal camera was positioned at a height of 1.5 m from the floor to the center of the camera lens and a horizontal distance of 4.9 m from the center of the participant's start position. The frontal camera position was positioned at a height of 1.4 m from the floor to the center of the camera lens and a horizontal distance of 4.2 m from the center of the participants' start position.

Upon arrival, demographic and anthropometric measures were obtained following which, participants were requested to don all firefighter bunker gear (22.7 kg) including self-contained breathing apparatus (SCBA) (18.1 kg). Full bunker gear including the SCBA was worn during completion of all components of the lifting task as firefighter bunker gear has been shown to change kinematic features associated with task performance and balance [20,21]. Furthermore, because our goal is to develop an evaluative process of movement that firefighters can implement during training and eventually, actual fire suppression activities, we deemed it critical that firefighters' don bunker during this protocol.

Participants were then asked to stand in a designated start position, marked on the floor as a "box" measuring 0.4 m x 0.3 m, facing the frontal camera position. The high-rise pack was placed on a marker 0.2 m from the right lateral edge of the start position "box" (see Figures 3.1, 3.2). Participants were instructed to lift the HRP to their shoulder and take 3 steps forward towards the frontal camera, using mechanics and pace similar to an emergency response situation and to initiate the task trial upon the researcher's verbal mark. Participants were permitted to move out of the start "box" as deemed necessary to lift the HRP. Video data from both the frontal and sagittal cameras was obtained during completion of the lifting tasks to allow later analyses using Dartfish ProSuite software. Video data was collected between April and May 2013.

<< Insert Figures 3.1 and 3.2 about here >>

*Data Extraction*

The examiner who conducted the data extraction received formal training through online Dartfish training sessions and had some experience using Dartfish ProSuite software.

The audio-video interleaves (AVI) files from the sagittal and frontal video cameras were downloaded into Dartfish Prosuite software. Because participant data was collected in a random order, the video files were cross-referenced and categorized by video identification number, participant ID and camera position in an Excel Spreadsheet. Each video was uploaded into the Dartfish Analyzer Module to extract kinematic outputs. Three methods were utilized to extract kinematic data: Angle Tracking, Positional Co-Ordinate Tracking and Single Frame analysis. Each of the three data extraction methods was used to analyze video obtained from both the Sagittal and Frontal camera positions.

(i) Angle Tracking

The “Analyzer” module in Dartfish was used to track hip and knee angles during completion of the lifting task. The hip angle was defined as the angle formed by one line connecting the lateral aspect of the acromion with the greater trochanter and a second line connecting the greater trochanter with the lateral aspect of the lateral femoral epicondyle. The knee angle was formed by connecting a line from the greater trochanter with the lateral femoral epicondyle and a second line connecting the lateral femoral epicondyle with the lateral malleolus. The anatomical landmarks were not palpable through the bunker gear and furthermore, we were unable to attach markers to the bunker gear due to fear of compromising the integrity of the bunker gear. Therefore, the anatomical landmarks were estimated in Dartfish software and identifying markers on bunker gear were used in attempt to standardize the angle segments and position.

Dartfish Analyzer supports a suite of drawing tools to facilitate kinematic analyses. The “Angle” drawing tool and “Data Table” were selected and “linked” to enable automatic entry and tracking of the angle in the Data Table during the lifting task. The angle “auto-track” feature was set at Fast (monitoring 20% of the video image) and joint angles were then tracked automatically by selecting “play”. The tracked joint angles and corresponding time were simultaneously recorded into a Data Table every 0.03 second. A methodological challenge using the auto-tracker feature is the angle often deviated from the defined angle position requiring a manual correction. When this occurred, the tracking feature was suspended, the incorrect angle was removed from the Data Table, the video was rewound to the frame where the error occurred and the angle-tracking feature was re-activated. The tracking feature was also suspended when the angle moved out of plane from the camera; the examiner conducting the data extraction and reliability analyses subjectively identified out-of-plane movement segments.

Visual inspection was used to identify the video frame representing participant’s initiation of movement towards the HRP (the start frame) and the video frame representing first heel strike as the participant initiated walking towards the frontal camera position (the end frame). These were recorded as the start and end frames of the angle tracking in an Excel spreadsheet to enable the reliability analyses. The Data Table, containing the individual participant tracked angles and corresponding timecode was exported into a separate Excel spreadsheet; individual participant’s angle data were consolidated into a separate Excel Spreadsheet, which was imported into SPSS for statistical analyses.

(ii) Positional Tracking

Similar methods used to track angle data were used to track positional co-ordinate data. Instead of using the angle drawing feature, the “Marker” tool was enabled to track hip and knee co-ordinate positional data, while firefighters performed the lifting HRP task. The marker was positioned centrally over the greater trochanter to track hip position and centrally over the patella to track knee position. As we were unable to palpate anatomical landmarks or place markers directly on the bunker gear, defining characteristics of the bunker gear were used in attempt to standardize marker placement. The top stripe on the coat of the bunker gear was used to standardize hip marker placement and the center of the knee patch was used to standardize knee marker placement. An object of known length was used to calibrate the video images converting the coordinate data into meaningful units of measurement.

The Data Table was selected from the Drawing Tools and was linked with the Marker to enable automatic recording of x,y co-ordinates of the joint positions. The auto-track feature was selected and set at “Fast” (monitoring 20% of the video image) and x,y co-ordinates of the joint position were recorded when “play” was selected. The tracked x,y coordinates and corresponding time were simultaneously recorded into a Data Table every 0.03 seconds. As noted with angle tracking, the marker often deviated from the defined position during the auto-tracking and required manual correction. When this occurred, the tracking feature was suspended, the incorrect coordinated data was removed from the Data Table, the video was rewound to the frame where the error occurred and the tracking feature was re-activated. A noted strength of using the tracking feature was observing plane of movement was not required as when using the angle-tracking feature.

Tracking was initiated when visual inspection determined the participant moved towards the high-rise pack and was terminated at first heel strike when the participant was identified walking towards the frontal camera position. The start and end frames were recorded in an Excel spreadsheet to facilitate reliability analyses. The Data Table was exported as a CSV file into an Excel spreadsheet, which was merged with all participant data by separating the x-coordinate and y-coordinate data. The consolidated data was then imported into SPSS for statistical analyses. Dependent measures were mean, standard deviation, coefficient of variation, maximum and minimum x and y-coordinates for both within and between participants.

(iii) Single Frame

Tracking errors, which required manual corrections, persisted during the tracking angle and positional data extraction. Subsequently, using single frame analyses was proposed as a solution where "vulnerable" postures are identified as those that occurred at transitions within the task or might be associated with increased risk of injury. Consequently, a protocol was developed to extract single frame angles associated with postures that were identified as "vulnerable" according to best practices supported by the provincial health and safety regulatory bodies[22]. Hip and knee angles were defined using the same methods as in Angle Tracking. Sagittal and frontal camera positions required different methods to extract single frame angles due to changes in participant position and orientation during task performance in the video frame.

(a) Frontal Camera Position: Visual inspection was used to identify the frame when the participant's left hand first contacted the high-rise pack. This was identified as a critical phase that initiated transfer of the high-rise pack from floor to shoulder. Various postures were demonstrated during this phase (i.e., bending/stooping at waist, bending at knees) exposing participants' to varying levels of biomechanical advantage during the lift phase. Once the video frame was identified and recorded, hip and knee angles were measured using the Angle drawing tool in the Analyzer module. The hip and knee angles were recorded in SPSS for statistical analyses.

(b) Sagittal Camera Position: The posture used in the frontal camera position could not be used for this analysis, as the hip and knee were not positioned sagittal to the frontal camera consequently a different "vulnerable" posture needed to be identified. Subsequently, it was observed that firefighters used low back extension when transferring the HRP onto their shoulder; visual inspection suggested this occurred when the HRP was at its highest vertical position. Consequently, it was determined that hip and knee angles assumed at this point in the lift posture were to be analyzed. The highest vertical point of the HRP was identified using the Dartfish Analyzer Module. A marker from the drawing tools was placed on the center of the pack and linked with the Data Table; y-coordinates of the marker were tracked in the Data Table. The data table was exported into Excel and the video frame with the highest y-coordinate (lowest value) was identified and recorded for reliability analyses. The video was played to this video frame in the Dartfish analyzer.

The angle drawing tool was used to measure hip and knee angles associated with this posture. The hip and knee angles were recorded in SPSS for descriptive and statistical analyses.

*Measures*.

Lower Extremity Kinematics.

A summary of angles and positional data obtained from all data extraction methods is provided in Table 3.2 (Frontal Camera Position) and Table 3.3 (Sagittal Camera Position). Left hip and knee angle and positional co-ordinate data was obtained from the Frontal Camera position; right hip and knee kinematics were obtained from the Sagittal Camera position.

<< Insert Table 3.2 about here >>

<< Insert Table 3.3 about here >>

Relative Hip Movement.

Hip positional data in isolation was not found to be clinically meaningful consequently, additional analyses was conducted to facilitate interpretation and application of this measure. The difference between participant maximum and minimum vertical hip displacement using y-axis coordinate data was calculated to identify hip vertical displacement. Hip vertical displacement was then normalized to participant height to identify relative hip movement.

All measures were computed using SPSS v. 20 (Chicago, IL).

2.4 Statistical Analyses.

*Reliability*

Intra-rater reliability was assessed for the examiner who conducted all data extraction from Time 1. The examiner repeated all three data extraction methods for each camera position analysis for Time 2 data. When determining Time 2 data from the frontal camera position, the examiner re-established the start and end frames for the tracking data extraction methods and the single frame analyses. Time 2 data from the sagittal camera position was determined using the same start and end frames for the tracking data extraction methods and the single frame analyses. When extracting data from the frontal camera position, the minimum time between Time 1 and Time 2 was 6 days and the average was 22.4 days. The minimum time between Time 1 and Time 2 data extraction from the sagittal camera position was 8 days; the average was 69.5 days. The overall mean minimum time between Time 1 and Time 2 was 6 days; the overall average was 43.3 days. Participant mean angle and positional coordinates of Time 1 and Time 2 hip and knee kinematic data were used for analysis.

Relative estimates of reliability were calculated using intra-class correlation coefficients for absolute agreement ($ICC_{2,1}$)[23]. Reliability coefficients were interpreted according to subjective categories[24] in which 0.4 were considered unacceptable, 0.41 to 0.60 moderate, 0.61 to 0.8 substantial and 0.81 to 1.0 excellent. Standard error of the measure (SEM) and minimal detectable difference (MDC) were calculated as estimates of absolute reliability. SEM, as an estimate of measurement error in angle (degrees) and positional co-ordinate (meters) was calculated using the following formula:

$SD_{(average)} \sqrt{1-ICC}$ [25]. $MDC_{90}$ = SEM x $\sqrt{2}$ x1.65 [26] was used to measure the amount of change in angle or positional co-ordinates required for an evaluator to be 90% certain the change was beyond the threshold due to measurement error.

**3. Results**

*Demographics*

The participant sample (n=12) for this study represented male (n=6) and female active firefighters with a mean age of 40.5 (+/- 8.3) years and 11.7 (+/- 7.6) years of firefighting service. Although sex/gender analyses were not conducted for the purposes of this study, gender-specific analyses of demographics indicate that male firefighters were older, taller, weighed more and had more years of service then their female counterparts (see Table 3.1). Male firefighters held the rank of Firefighter (67%) and Captain (33%); 100% of female participants held the rank of Firefighter.

*Knee and Hip Kinematics*

Frontal Camera Position:

Descriptive statistics of left knee and hip kinematics using angle tracking, positional tracking and single frame data extraction from the Frontal Camera position are shown in Table 3.2. Using the angle tracking data extraction method from the frontal camera position, the mean left knee angle (mean of Time 1 and Time 2) was 150.2° (SD = 11.5°) and the mean left hip angle (Time 1 and Time 2) was 98.5° (SD = 16.7°). Using the positional tracking data extraction method, the average relative change in left hip movement was 17.6% (SD = 4.4%) of participant height. Using single frame data extraction, the mean left hip angle (Time 1 and Time 2) was 56.6° (SD= 14.0°) and the mean left knee angle was 111.8° (SD = 26.5°).

Sagittal Camera Position:

Descriptive statistics of the right knee and hip kinematics extracted from the sagittal camera position are shown in Table 3.3. Using the angle tracking data extraction method from the sagittal camera position, the mean right knee angle (mean of Time 1 and Time 2) was 148.3° (SD = 12.8°) and the mean left hip angle was 144.5° (SD = 18.8°). Using positional tracking data extraction methods, the average relative change in left hip movement was 19.6% (SD = 12.7%) of participant height. The mean left hip angle (Time 1 and Time 2) using single frame data extraction method was 167.3° (SD= 6.6°) and the mean left knee angle was 148.7° (SD = 22.4°).

*Reliability for Knee and Hip Kinematics*

Frontal Camera Position:

As shown in Table 3.4, relative reliability was excellent ($ICC_{2,1}$ = 0.85 - 0.97) for knee measures using the angle tracking and single frame data extraction methods. Relative reliability for hip measures was excellent ($ICC_{2,1}$ = 0.84 – 0.97) for positional tracking and single frame data extraction and substantial ($ICC_{2,1}$ = 0.72) when using the angle tracking method. Absolute reliability reflected in SEM and MDC are smaller for knee angle tracking then hip angle tracking and similar when using single frame data extraction.

<< Insert Table 3.4 about here >>

Sagittal Camera Position:

Table 3.5 shows excellent relative reliability ($ICC_{2,1}$ = 0.93 - 0.94) for knee measures using angle tracking and single frame data extraction methods. Relative reliability for hip measures was excellent ($ICC_{2,1}$ = 0.81 - 0.98) for angle and positional tracking extraction methods and substantial ($ICC_{2,1}$ = 0.78) using single frame data extraction. Absolute reliability using SEM and MDC is smaller for knee angle tracking then hip angle tracking. Using single frame data extraction, SEM and MDC are smaller for hip angle then knee angle.

<< Insert Table 3.5 about here >>

**4. Discussion**

Study results demonstrated that lower extremity kinematic measures, can be reliably extracted using Dartfish angle tracking, positional tracking and single frame data extraction methods, during a field-controlled firefighting task, using video-based inputs from frontal and sagittal camera positions. These results support previous research[13,15] that also identified reliable lower extremity kinematic data extraction using Dartfish however, we were able to demonstrate these same measurement properties in an applied occupational context with fewer positional and task controls. Furthermore, we identified lower extremity movements associated with a firefighting lift task providing new insights into the postural requirements associated with this task.

*Lower Extremity Amplitudes*

Our study results for angle tracking of knee and hip angles identified that on average, participants performed this lifting task in knee ($\overline{X}_F = 150°$; $\overline{X}_S = 148°$) and hip partial flexion ($\overline{X}_F = 98°$; $\overline{X}_S = 144°$). A full range of knee motion was required from full knee flexion (24° to 81°) to no knee flexion (180° = standing) during completion of the lifting task. Hip tracking angle analyses also identified a full range of motion from full hip flexion (25° to 38°) to no hip flexion (180° = standing). Relative hip movement identified that participants' hip moved on average 17% to 20% of their overall height; minimum 4% and maximum 50% of height. These results suggest that relative hip movement as a single construct of lower extremity posture may provide as much information about knee and hip kinematics as knee and hip kinematics individually. Further research directed to identify relationships between these constructs is underway.

Previous studies [21,27] have also analyzed firefighter kinematics but using highly instrumented laboratory settings involving multiple cameras and force plates. The study results identified that firefighter equipment affects balance [21]and gait patterns [27]with implications for increased risk of falling. Although our study was not positioned to identify balance and gait related to firefighting task performance, study results support that firefighter task performance can be quantified with less experimental control extending the capacity of research aimed to identify firefighter posture and kinematic from laboratory occupational health research to applied occupation health research context. The next phase of research will need to extend our measurement approach and identify predictors of firefighter task performance and injury.

*Reliability*

An important consideration when interpreting our study results is that participants were not confined to a plane of movement corresponding to the camera position. The HRP was located to the right of each participant and each participant was required to start the lifting task in a standardized position facing the frontal camera. Therefore, analyses conducted from the sagittal camera position involved most participants rotating in the transverse plane, towards the high-rise pack resulting in analyses conducted from a frontal plane perspective; conversely, analyses of video inputs obtained from the frontal camera position involved participants rotating into a sagittal perspective. Therefore, comparison between previous research[13–15] and our findings on relative and absolute reliability should focus on results from the frontal camera position although discussion of findings from both the frontal and sagittal camera positions is provided.

**Relative Reliability.** The present study results extends previous research[13–15] that identified Dartfish as a reliable measurement approach to analyze lower extremity movements associated with functional tasks. Our study findings are unique as we demonstrated ability to replicate the high measurement properties using two camera positions, multiple data extraction methods and during a field-controlled firefighting task where participants donned full firefighting equipment and task performance parameters were not controlled. Norris et al.[13] and Allen et al.[15] both analyzed hip and knee movements using similar protocols to define anatomical landmarks, when designing the lift task protocol including camera position and developing data extraction methods (i.e., angle tracking). Norris et al.[13] identified high intra-rater reliability of both hip flexion

(ICC = 0.99, 95% CI: 0.98, 0.99) and knee flexion (ICC = 0.98, 95% CI: 0.96, 0.99) in contrast to Allen et al.[15] who identified lower intra-rater reliability for hip flexion (ICC = 0.26, 95% CI: -0.27, 0.33), compared to knee flexion (ICC = 0.95, 95% CI: 0.88, 0.97). When using the angle tracking method our study results also identified lower hip angle intra-rater relative reliability compared to knee angle when analyzing video inputs from both the frontal camera position (ICC = 0.72, 95% CI 0.30, 0.91 vs. ICC = 0.85, 95% CI 0.50, 0.96) and the sagittal camera position (ICC = 0.82, 95% CI 0.51, ICC = 0.96 vs. 0.93, 95% CI 0.78, 0.98). One explanation for the difference in relative reliability results between our study and Norris et al.[13] is the context of the lifting task.

The lifting task performed in our study and in Allen et al.[15] was complex, requiring strength and endurance capacity compared to the lifting task in Norris et al.[13]. For example, Norris et al.[13] required participants to lift a box with handles from floor to waist level, loaded with weight equal to 30% of participant's maximum lifting capacity (MLC). This percentage of MLC was specifically chosen to reduce the variability in hip-knee coordination. The lifting task in Allen et al.[15] required three repetitive lifts from waist to shoulder, using an empty box with handles; following completion of the three repetitions, weight was progressively added to the box. This protocol was terminated by the assessor when it was determined that unsafe or compensatory movements were being employed, participants reached their maximum heart rate limit or when the participant self-terminated the task. Lifting tasks in both studies were conducted in laboratory settings with participants wearing skin-based markers to facilitate kinematic analyses. The lifting task in our study required participant's to negotiate lifting the high-rise pack

(HRP) from floor to shoulder. The HRP lacks defined structure and participants negotiated this lift in firefighter bunker gear, contributing to increased task complexity. It is likely the complexity of lift task performed in our study contributed to increased variability in hip movement and lower relative reliability in tracking hip angle.

Our study results also suggest that hip positional tracking using x,y coordinates resulted in higher relative reliability than tracking hip angle. Furthermore, tracking hip angle from the frontal camera position, which captured individuals rotating in a transverse plane towards the pack resulted in the lowest relative reliability and highest absolute reliability. Measuring hip angle offers more error sources through positioning and tracking hip angle through transverse plane rotations using a two-dimensional movement analysis system. Although angle of movement is a more clinically relevant outcome, normalizing body segment displacement to participant height as computed in our study with hip vertical displacement, converts body segment displacement to a more clinically relevant outcome. Our findings suggest that using positional coordinates to track body segments that rotate through the transverse plane (i.e., hip, shoulder) addresses the limitation of assessing rotating body segment movements in 2-dimensions and improves relative reliability.

**Absolute Reliability.** In addition to high relative reliability, the absolute reliability measured by standard error of measurement (SEM) and minimal detectable difference (MDC) in hip displacement and knee angle is considerably lower then hip angle. Absolute reliability for tracking knee and hip angle indicated that when observing movement from a frontal camera position, an ergonomist could be 95% confident that a change of at least 10.5° and 20.8° respectively, between two measures would reflect a true change in score. Similar findings regarding absolute reliability were identified for tracking knee and hip from the sagittal camera angle. When considering hip vertical displacement, more than a 5% change in relative hip movement will be needed to reflect a true change in hip displacement from the frontal camera position and 13% change from the sagittal camera position.

An unexpected finding was that absolute reliability using all data extraction methods for tracking hip and knee kinematics (i.e., angle and positional coordinates) reflected similar proportional changes in both the frontal and sagittal camera positions. We anticipated that hip and knee kinematics would be more reliable when extracted from the frontal camera position as this approach was met with fewer methodological challenges. These findings suggest however, that angle and positional co-ordinate data can be reliably extracted using either frontal or sagittal camera position within the methodological constraints reviewed herein.

Analyses of single frame angle data extraction of the hip and knee from the frontal camera position support excellent relative reliability and acceptable absolute reliability. Sagittal camera angle analyses identified more variability in reliability. Substantial relative reliability and appropriate absolute reliability of hip angle and excellent relative reliability and moderate absolute reliability of knee angle were identified. Using the single frame data extraction method of hip angle, a difference of more then 5.8° from a frontal camera perspective and 3.3° from a sagittal camera perspective would be considered a clinically relevant difference. When considering knee angle, more then a

6.1° and 13.1° difference from the frontal and sagittal camera perspectives respectively would be determined clinically important. Our study findings were compared to research that used goniometry to identify knee angles[28] as this method most closely replicates single frame angle extraction in Dartfish. For example, Norris et al.[13] used goniometry to identify concurrent validity of Dartfish when identify hip and knee angles. Recent research used goniometric measures to identify knee flexion and extension angles in patients with a total knee arthroplasty (TKA)[28]. Their study identified a clinically meaningful difference of 6.6° in intra-rater reliability for knee flexion using goniometry, which is similar to our findings in the frontal camera perspective (6.1°) but not the sagittal camera perspective (13.1°). Interestingly hip angle absolute reliability for single frame data extraction was lower then knee angle absolute reliability in both frontal and sagittal camera angles. Rationale for this discrepancy is not clear although the variability in task performance between participants may contribute to this difference as well as difficulty identifying kinematics through the transverse plane in the sagittal camera perspective.

*Clinical Implications*

Analyzing reliability associated with kinematic outcomes of occupational task performance provides useful information about the way movements are performed and the clinically important difference in the measurement approach. Our study results suggest that using Dartfish to analyze occupational task performance from video images provides a valid, reliable measurement approach to identify postural demands associated with a field-controlled firefighting task. The important implication of this study is that reliable kinematic measures can be obtained using a protocol with reduced scientific vigour. Ergonomists are able to import video data and use this approach to identify task demands and create individualized task-specific standards that would be useful in identifying the impact of injury prevention strategies and planning return-to-work. Based on our study results, when analyzing lower extremity postures during occupational task performance using Dartfish the following recommendations are suggested:

(a) Consider camera position relative to body segment movements from which data extraction is anticipated. Sagittal perspectives facilitate data extraction during complex movements when body segments rotate through multiple planes.

(b) Use positional coordinates when tracking hip position. To improve clinical relevance of outcome, convert to anthropometric reference (i.e., body height).

(c) Use single frame data extraction when identifying postures associated with a point of interest during task performance.

(d) Enable the "suspend tracking" function when markers are occluded during angle or positional coordinate tracking.

(e) Angle tracking is useful when determining the range-of-motion associated with task performance however, is associated with reduced reliability when tracking body segments moving through the transverse plane (i.e., hip postures).

Dartfish software demonstrates promise as a movement analysis tool for use in applied occupational health research when identifying lower extremity postures during a field-controlled occupational task. Additional research that extends this measurement approach to more complex, continuous tasks is required before expanding application in applied occupational health research.

*Strengths and Limitations*

The primary strength of our study is the unique context and approach that extends current research using this methodology to identify kinematics associated with occupational task performance. Specifically, we integrated multiple data extraction methods associated with Dartfish, using video inputs from multiple camera positions and identified excellent reliability in an applied occupational context. Our study findings have important implications for utility in ergonomics, return-to-work and occupational health where objective measures of posture associated with task performance are required.

The primary limitation of our study was the relatively small sample size although we were able to identify appropriate reliability measures of knee and hip postures. We anticipate the strength of these findings would be enhanced with a larger sample size.

An additional limitation of this study was the lack of scientific standardization in task performance and in marker placement, which was intentional, as the study purpose was to evaluate Dartfish data extraction methods for lower extremity kinematics in an applied occupational context. Our results suggest that standardizing data extraction methods is more important for use with this measurement approach then using a marker-based system. We presume that our findings would be as good if not stronger under more controlled experimental conditions.

The focus of this study was intra-rater reliability. The rater for this study was experienced in conducting biomechanical analyses and had some experience using Dartfish software. It is likely that users implementing this approach in occupational contexts may not have the same experience with Dartfish as the rater. Although a previous study[13] using Dartfish under tightly controlled experimental conditions identified high relative and absolute reliability between experienced and non-experienced raters. Regardless, studies that consider rater experience with biomechanical analyses and Dartfish software would provide important insights into the generalizability of our findings across raters. Additional studies expanding these findings to applied, occupational contexts with different rater experiences are necessary to strengthen the measurement properties of this approach.

A further limitation of this study was focus on lower extremity postures during this firefighting lift task. Future research identifying reliability of upper extremity postures in occupational contexts is recommended to confirm that this measurement approach can be applied to assessing whole body movements.

## 5. Conclusions

The purpose of this study was to measure the reliability of multiple data extraction methods supported in Dartfish software to identify lower extremity kinematics associated with a field-controlled firefighting lift task, using multiple camera perspectives. Our study replicated reliability of lower extremity angle measures identified in previous research[13–15] and identified recommendations for using Dartfish to identify lower extremity postures in an applied, occupational context. Overall, the study findings support that Dartfish offers a reliable, accessible platform to measure video-based inputs of lower extremity kinematics associated with a firefighting lift task. The recommendations support that Dartfish demonstrates promise as an approach that might bridge the gap between laboratory-based occupational research, applied occupational research and ergonomic practice.

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## Manuscript Tables

Table 3.1 Participant Demographics

| | Age (years) | Height (m) | Weight (lbs.) | Tenure |
|---|---|---|---|---|
| Male (n=6) | 45 (8.6) | 1.77 (0.12) | 203.8 (12.4) | 16.3 (7.8) |
| Female (n=6) | 36 (5.4) | 1.62 (0.04) | 148.5 (27.7) | 7.0 (3.6) |
| Overall | 40.5 (8.3) | 1.72 (0.10) | 176.2 (35.4) | 11.7 (7.6) |

[ $\overline{X}$ **, (**SD)]

Table 3.2 Frontal Camera: Lower Extremity Amplitudes
* Hip, Knee refer to participants' *left* side. *Mean and SD represent the mean of the participant mean values. 'Max' is the maximum value of the participant's maximum outcome of the variable of interest and 'min' represents the minimum value in participants' range in the variable of interest.*

| Variable | Time 1 | | Time 2 | |
|---|---|---|---|---|
| | Mean (SD) | Max. / Min. | Mean (SD) | Max./Min. |
| Knee angle (deg.): Tracked | 148.4 (12.1) | 179.9 / 81.2 | 152.0 (11.2) | 180.0 / 81.3 |
| Hip angle (deg.): Tracked | 100.2 (15.4) | 179.6 / 37.7 | 96.8 (18.4) | 179.8 / 33.5 |
| Hip position (m): Tracked | | | | |
| Horizontal | 2.16 (.20) | 2.65 / 1.67 | 2.21 (0.22) | 2.71 / 1.84 |
| Vertical | 1.42 (0.11) | 1.79 / 1.12 | 1.40 (0.13) | 1.80 / 1.12 |
| Hip Vertical Displacement (m) | 0.31 (0.07) | 0.41/0.15 | 0.30 (0.08) | 0.43 / 0.15 |
| Relative Hip Movement (%) | 17.8 (4.1) | 23 / 8 | 17.5 (4.8) | 25 / 8 |
| Hip angle (deg.): Single Frame | 57.2 (14.1) | 89.5 / 40.2 | 56.1 (14.5) | 86.4 / 37.2 |
| Knee angle (deg.): Single Frame | 113.1 (27.4) | 168.2 / 80.7 | 110.6 (26.9) | 164.2 / 78.3 |

Table 3.3 Sagittal Camera: Lower extremity amplitudes
*Hip and knee refer to participant's *right* side. *Mean and SD represent the mean of the participant mean values. 'Max' is the maximum value of the participant's maximum outcome of the variable of interest and 'min' represents the minimum value in participants' range in the variable of interest.*

| Variable | Time 1 | | Time 2 | |
|---|---|---|---|---|
| | Mean (SD) | Max. / Min. | Mean (SD) | Max./Min. |
| Knee angle (deg.): Tracked | 147.7 (13.5) | 180.0 / 24.0 | 149.0 (12.7) | 179.8/36.41 |
| Hip angle (deg.): Tracked | 139.9 (20.0) | 179.0 / 25.8 | 149.2 (17.2) | 180.0/19.36 |
| Hip position (m): Tracked | | | | |
| Horizontal | 2.4 (0.3) | 3.3 / 1.8 | 2.4 (0.2) | 3.6 / 1.8 |
| Vertical | 1.8 (0.3) | 2.7 / 1.4 | 1.8 (0.3) | 2.6 / 1.4 |
| Hip Vertical Displacement (m) | 0.4 (0.2) | 0.8 / 0.1 | 0.33 (0.21) | 0.8 / 0.1 |
| Relative Hip Movement (%) | 20.4 (14.4) | 46 / 4 | 18.8 (11.4) | 44 / 6 |
| Hip angle (deg.): Single Frame | 166.2 (7.2) | 173.8/147.4 | 168.5 (6.0) | 175.0/154.3 |
| Knee angle (deg.): Single Frame | 148.2 (20.3) | 175.4 / 93.7 | 149.2 (25.4) | 170.9 / 72.6 |

Table 3.4 Frontal Camera: Relative and Absolute Reliability of Lower Extremity Amplitudes

| Variable | $ICC_{2,1}$ | 95% CI | SEM | $MDC_{90}$ |
|---|---|---|---|---|
| Knee Angle | 0.85 | 0.50, 0.96 | 4.5 deg. | 10.5 deg |
| Hip Angle | 0.72 | 0.30, 0.91 | 8.9 deg. | 20.8 deg |
| Hip Position | | | | |
| Horizontal | 0.90 | 0.67, 0.97 | 0.06 m | 0.14 m |
| Vertical | 0.85 | 0.56, 0.95 | 0.05 m | 0.12 m |
| Hip Vertical Displacement | 0.86 | 0.57, 0.96 | 0.02 m | 0.07 m |
| Relative Hip Movement | 0.84 | 0.52, 0.95 | 2% | 5% |
| Hip Angle (single frame) | 0.97 | 0.89, 0.99 | 2.5 deg. | 5.8 deg |
| Knee Angle (single frame) | 0.97 | 0.91, 0.99 | 2.6 deg. | 6.1 deg |

Table 3.5 Sagittal Camera: Relative and Absolute Reliability of Lower Extremity Amplitudes

| Variable | $ICC_{2,1}$ | 95% CI | SEM | $MDC_{90}$ |
|---|---|---|---|---|
| Knee Angle | 0.93 | 0.78, 0.98 | 3.5 deg | 8.2 deg |
| Hip Angle | 0.82 | 0.51, 0.96 | 7.9 deg. | 18.4 deg |
| Hip Position | | | | |
| Horizontal | 0.96 | 0.86, 0.99 | 0.01 m | 0.02 m |
| Vertical | 0.98 | 0.92, 0.99 | 0.04 m | 0.09 m |
| Hip Vertical Displacement | 0.84 | 0.54, 0.95 | 0.09 m | 0.21 m |
| Relative Hip Movement | 0.81 | 0.48, 0.94 | 6% | 13% |
| Hip Angle (single frame) | 0.78 | 0.36, 0.93 | 1.4 deg | 3.3 deg |
| Knee Angle (single frame) | 0.94 | 0.79, 0.98 | 5.6 deg | 13.1 deg |

**Manuscript Figures**

Figure 3.1: Frontal Camera Position

Figure 3.2 Sagittal Camera Position

## Chapter Four

**Title: Reliability of a video-motion analysis system to identify upper extremity postures and head movement during performance of a field-controlled firefighting lift task.**

Authors: Kathryn E. Sinden, Joy C. MacDermid, Thomas R. Jenkyn, Sandra Moll

This paper is being submitted to *Applied Ergonomics* for review and publication consideration.

**Abstract.**
Upper extremity workplace injuries are complex and represent a significant burden to individuals and organizations. Developing strategies that integrate tools used by ergonomists such as videotaping with kinematic analysis might provide valuable insights into the mechanisms of upper extremity workplace injuries. Dartfish is movement analysis software that uses video-based inputs to enable kinematic analysis. Dartfish has been previously shown to be reliable when analyzing lower extremity kinematics associated with a firefighting lift task. Our study identified the relative and absolute reliability of Dartfish for assessing upper extremity and head movement during a firefighter lift task. Video was obtained from sagittal and frontal camera perspectives. Analysis used three data extraction methods: angle tracking, positional co-ordinate tracking and single frame angle analysis. Relative reliability was determined using intra-class correlation coefficients ($ICC_{2,1}$) and absolute reliability was measured using standard error of measurement (SEM) and minimal detectable change ($MDC_{90}$). Moderate relative reliability was determined for tracking elbow angle ($ICC_{2,1}$=0.52 - 0.67) and poor ($ICC_{2,1}$=0.39) to excellent ($ICC_{2,1}$ = 0.87) for tracking head position, depending on camera perspective. Relative reliability for tracking horizontal ($ICC_{2,1}$ = 0.94 – 0.98)

hand position and vertical right hand position (ICC2,1= 0.96) was excellent. Relative reliability for relative head vertical displacement and relative hand horizontal displacement was higher when extracted from the frontal camera position ($ICC_{2,1}$=0.86–0.96) compared to the sagittal camera position ($ICC_{2,1}$ = 0.74 – 0.69). Relative reliability for single frame angle analysis was excellent in both camera perspectives. Absolute reliability was highest for tracking angles and lowest for determining anatomical co-ordinate position. Recommendations for using Dartfish to analyze upper extremity kinematics during a field-controlled firefighting lift task are provided including use of positional hand co-ordinates to identify shoulder motion.

## 1. Introduction

Occupational health is a relevant concern as over half a million workers in Canada experienced at least one activity limiting work-injury in 2003[1]. Furthermore, the most frequently injured body part was the hand (28%); with the shoulder, elbow and wrist in combination comprising an additional 16.1% of injuries[1]. Although tools and observational methods exist to facilitate injury risk assessment of the upper extremity[2,3] their use by ergonomists, and health and safety professionals is limited. Ergonomists endeavour to identify context to apply these methods, and there is a perceived level of expertise required to implement the tools[3,4]. Although these same observational methods are often used in applied occupational health research to identify biomechanical demands associated with work tasks, practicing ergonomists depend more on indices of injury risk related to manual material handling and strength (i.e., NIOSH lifting equation[5]) and employ use of measurement tools such as tape measures, force gauges and video to assess task demands[3,4]. Developing evidence-based strategies to assess occupational task performance that incorporate preferences of ergonomists would ensure methods are contextually relevant. Furthermore, this approach may bridge the gap between tools used by ergonomists when assessing occupational task performance related to injury risk and those used by researchers to advance understanding of the relationship between occupational injury risk exposures and work health.

Dartfish (Lausanne, Switzerland) is movement analysis software, designed to analyze movements and postures obtained from video-based inputs. Dartfish software enables users to quantify postures using a variety of kinematic measures (i.e., angles, positional coordinates, speed) and translates the analyses into outputs that translate to the end-user. A primary advantage of establishing Dartfish as a feasible tool to measure kinematics in occupational contexts is that video, as preferred tool of practicing ergonomists[3], can be used to obtain quantitative measures related to task performance and movement. Furthermore, Dartfish is portable and can be used to provide immediate feedback to workers in any occupational context. The implications are that employers and ergonomists can provide immediate visual and kinaesthetic feedback to workers following modifications to components that influence task performance. This approach may also have potential to evaluate changes in task performance following an injury and / or during the return-to-work phase of rehabilitation following an injury or illness.

Although there are multiple benefits to this measurement approach, potential limitations also exist. For example, the kinematic analysis used in Dartfish is two-dimensional however movements in occupational contexts are complex and often occur in three planes of movement. Therefore, reliability may be compromised when using Dartfish to analyze inter-planar movements. Furthermore, it is challenging to secure visible markers used to enable standardized kinematic analyses, to clothing and / or equipment. Consequently, measurement precision associated with assessing movement in occupational contexts may also be limited by clothing, personal protective equipment, tools and equipment used by workers. Strategies to address these limitations are needed to improve the measurement properties of Dartfish before using this approach in field-based applications.

Previous research has demonstrated that Dartfish is a reliable tool to extract kinematic, lower extremity data in highly controlled laboratory settings[6–8]. This research provided important foundational work upon which to build a measurement approach for use in more applied settings. Recent research conducted by the study authors, has used Dartfish to analyze lower extremity kinematics during a field-controlled firefighting lift task[9]. Although excellent reliability for measuring knee angles was established, methodological challenges particularly when extracting hip angle over time were identified. The study results suggested that reliability was compromised when having to track a two-dimensional angle through the transverse plane[9]. Subsequently, a series of recommendations to facilitate future research in similar contexts including using positional data to capture multi-planar body segment movements were provided. These recommendations were used to inform the analytical methods used in the current study, although it was unclear how the measurement properties would translate when analyzing upper extremity movements within a similar context.

Few studies have used Dartfish to analyze upper extremity movements. Melton et al.[10] used Dartfish to analyze shoulder movements in both healthy and patient populations. Dartfish was found to be reliable however, methodological issues with respect to angle tracking errors and the time required to analyze video were identified. Furthermore, task performance was restricted to the scapular plane and skin-based markers were used to facilitate analysis, two primary methodological limitations of this study when translating to applied occupational health research. Although reasonable in a laboratory setting, the protocol would not be feasible in applied occupational contexts where task performance is multi-planar and variable and workers are required to wear clothing and / or personal protective equipment. Khadilkar et al.[11] extended this research and used Dartfish to establish upper extremity kinematics in more complex movements associated with performing activities of daily living described by the Disability of the Arm, Shoulder and Hand (DASH) questionnaire[12]. This study established high test-retest reliability with multi-planar movements however lower reliability was observed when extracting shoulder kinematics associated with tasks involving multiple planes of movement (i.e., opening a tight jar). Although this study applied Dartfish to functional tasks, the study continued to employ laboratory measurement techniques that are less applicable to applied occupational contexts.

Consequently, the study purpose was to identify the reliability of Dartfish for extracting upper extremity postures and head movement during a field-controlled firefighting lift task. Based on previous research[10,11], we anticipated that tracking shoulder angle would be associated with more methodological challenges and poorer reliability. Based on our previously conducted research using positional co-ordinate data to track multi-planar lower extremity movements[9], we hypothesized that tracking positional co-ordinate data of the hand and conducting single frame angle analysis would address limitations with the angle tracking method with respect to shoulder movements.

## 2. Methods

### 2.1 Design

This study used intra-observer reliability to identify the reproducibility of Dartfish when extracting upper body kinematics during a field-controlled firefighting lift task.

Two data extraction times were used to calculate intra-rater reliability across three Dartfish data extraction methods (angle tracking, positional coordinate tracking and single frame analysis), from two camera positions for the elbow, shoulder and hand position.

2.2 Participants

Fully active, fit-for-duty firefighters from a fire service in Southwester, Ontario volunteered and consented to participate (n=12). The fire service consists of 471 active duty firefighters; 3% are female firefighters. To ensure female firefighter representation, we purposively included all consenting female firefighter participants (n=6); a random sample of male firefighter participants was recruited into this study (see Table 4.1). Ethics approval was obtained from the Hamilton Integrated Research Ethics Board (HIREB) (Appendix B).

<< Insert Table 4.1 about here >>

2.3 Procedures

*Context.*

All study protocols (Appendix C) were conducted in the firefighter's training facility. The training facility accommodates four (4) fire trucks, allows access to equipment used in fire suppression and emergency response task; the training facility also facilitate implementation of field-controlled firefighting training protocols.

*Task: Lifting a High Rise Pack (HRP).*

Firefighters have identified lifting a HRP as a critical task in their job performance and associate lifting a HRP with higher injury rates. A HRP (19.5 kg.) consists of two lengths of firefighting hose (15 m each; 30 m total) including an attached nozzle and tools (i.e., wrench, couplings and other equipment). The HRP is used by firefighters when responding to structural fires (i.e., large warehouses, high rise) that contain hose cabinets and / or stand pipe systems. The HRP is lifted and carried from the truck to locations within a structure. Although functional components associated with this task include lifting, carrying, walking and climbing stairs, the components assessed during this study were lifting the HRP from floor level and walking with the HRP. Previous research[10,11,13] measuring reliability of Dartfish to measure upper extremity kinematics have focussed on above shoulder reaching tasks; our study protocol extends this research as the lifting task extends from floor level to above shoulder.

*Data Acquisition.*

Complete data acquisition methods have been previously reviewed[9]. Briefly, one digital video camera (JVC HD Everio GZ-VX700, Full HD, AVCHD) was positioned on a tripod facing participants in the sagittal plane and a second video camera (JVC HD Everio GZ-VX700, Full HD, AVCHD) was positioned facing participants from the frontal plane. Firefighter participants were requested to don their personal firefighter bunker gear (22.7 kg) including self-contained breathing apparatus (SCBA) (18.1 kg) during completion of all components of the lifting task.

Participants initiated the lift task from a designated start position, marked on the floor as a "box" facing the frontal camera position. The high-rise pack was placed on a marker positioned 0.2 m from the lateral edge of the start position, to the right of participants (see Figures 4.1, 4.2). Participants initiated each lifting task trial upon the researcher's verbal mark. Participants were permitted to move out of the start "box" as deemed necessary to lift the HRP. Video data from both the frontal and sagittal cameras was obtained during completion of the lifting tasks to facilitate later analyses using Dartfish ProSuite software.

<< Insert Figures 4.1 and 4.2 about here >>

*Data Extraction*

Data extraction methods have been reviewed in detail previously[9]. Briefly, the examiner who conducted the data extraction received formal training through online Dartfish training sessions and had some previous experience using Dartfish analytics.

The audio-video interleaves (AVI) files from the sagittal and frontal video cameras were downloaded into Dartfish software. Three methods available in the Dartfish Analyzer Module were used to extract kinematic data: Angle Tracking, Positional Tracking and Single Frame analysis. Participant video images from both the Sagittal and Frontal camera positions were analyzed using each of the three data extraction methods (see Appendix D).

(i) Angle Tracking

The "Analyzer" module in Dartfish was used to track the elbow angle from video images obtained from both the sagittal and frontal cameras. The elbow angle was formed by connecting a line from the shoulder joint center of rotation with the elbow joint center of rotation and a second line connecting the elbow joint center of rotation with the center of the hand. Because of limitations with palpating anatomical landmarks through bunker gear and attaching markers to the bunker gear, the anatomical landmarks were estimated in Dartfish software. Identifying markers on bunker gear were used to facilitate standardization of the defined angle segments and position.

The “Angle” drawing tool in the Dartfish Analyzer module and “Data Table” were selected and “linked” to enable automatic entry and recording of the angle in the Data Table during the lifting task. The angle “auto-track” feature was set at Fast (monitoring 20% of the video image) and joint angles were then automatically recorded when “play” was selected. The tracked joint angles and corresponding time were simultaneously recorded into a Data Table every 0.03 second. Angle tracking was suspended when deviations of the Dartfish markers from the defined angle position occurred and when the angle moved out of plane from the camera; the examiner conducting the data extraction and reliability analyses subjectively identified out-of-plane movement segments.

Visual inspection was used to identify start and end frames of the task. The video frame representing participants’ first initiation of movement towards the HRP was identified as the start frame and the video frame documenting first heel strike as the participant initiated walking towards the frontal camera position was identified as the end frame. These were recorded in an Excel spreadsheet to enable the reliability analyses. The Data Table, containing the individual participant tracked angles and corresponding timecode was exported into a separate Excel spreadsheet; individual participant’s angle data were consolidated into a separate Excel Spreadsheet, which was imported into SPSS for statistical analyses.

(ii) Positional Tracking

Similar methods used to track angle data were used to track positional co-ordinate data. A Marker from the Dartfish drawing tools was used to track head and hand co-ordinate positional data. The marker was positioned centrally over the midline of participants' facial structures to track head position and centrally over the dorsal aspect of the hand to track hand position. An object of known length was used to calibrate the video images converting the coordinate data into meaningful units of measurement.

The same methods used to track angle were used to track positional data coordinates. Observing plane of movement was not required when tracking x,y positional co-ordinates which was noted as a methodological strength of using the positional tracking feature versus the angle tracking feature.

As during angle tracking, positional tracking was initiated when visual inspection determined the participant moved towards the high-rise pack and was terminated at first heel strike when the participant was identified walking towards the frontal camera position. The start and end frames were recorded in an Excel spreadsheet to facilitate the reliability analyses. The Data Table with positional coordinate data was exported as a CSV file into an Excel spreadsheet; x- and y-coordinate data were separately merged with all comparable participant data. The consolidated data was then imported into SPSS for statistical analyses. Dependent measures were mean, standard deviation, coefficient of variation, maximum and minimum x and y-coordinates for both within and between participants.

(iii) Single Frame

Single frame angle analysis was proposed as a solution to the methodological challenges associated with angle tracking (i.e., identifying out-of-plane movements, adjusting deviations from the angle tracking). An approach was established to simulate analysis conducted by an ergonomist when identifying kinematics associated with an "at-risk" posture. An "at-risk" posture was identified as one occurring during biomechanical transitions within the task that might be associated with increased risk of injury, according to best practices supported by occupational health and safety groups in Ontario [14]. Shoulder angle was formed using similar methods as used in Melton et al.[10]; a marker placed centrally over the glenohumeral joint was connected with a marker placed centrally at the elbow center of rotation and the elbow marker was connected with a marker placed centrally over the hip center of rotation. The elbow angle was defined using the same methods as in Angle Tracking. Sagittal and frontal camera positions required different methods to extract single frame angles due to changes in participant orientation during task performance in the video frame.

(a) Frontal Camera Position:

It was observed that firefighters used elevated, external rotation of the left shoulder when placing the HRP on their shoulder; visual inspection suggested that this occurred when the left elbow was at its highest vertical position during the lift. It was determined that the angle of left elbow and shoulder at this position in the lift represented an awkward posture with associated risk of injury[14] and would be analyzed using a single frame analysis approach. The highest vertical point of the participant's left elbow was identified using a Marker from the Dartfish drawing tools to track the y-coordinate positional data. The Dartfish marker was placed centrally on the elbow center of rotation and linked with the Data Table; y-coordinates of the marker were tracked in the Data Table. The data table was exported into Excel and the video frame with the highest y-coordinate was identified and recorded for analysis. The video was played to this video frame in the Dartfish Analyzer module. The angle drawing tool was used to measure participant left shoulder and elbow angles associated with this posture. Shoulder and elbow angles were recorded in SPSS for descriptive and statistical analyses.

(b) Sagittal Camera Position:

The frame used in the frontal camera position for single frame analysis could not be used for analysis of video obtained from the sagittal camera, as the shoulder and elbow were not positioned to allow in-plane analysis. Furthermore, participants' right shoulder was in plane only during the initial standing posture in the designated start position; therefore, shoulder analysis was removed from the single frame analysis of the sagittal camera position. Although participants' right elbow joint was visible during tracking, it moved out of plane frequently and a "high risk" position where the right elbow was in plane could not be identified. It was observed that the left elbow moved through various awkward postures[14] when transitioning the HRP from floor to shoulder. Consequently an in-plane, "at risk" posture was identified as the point in task when the left arm was at its highest vertical point before moving out of plane for analysis. The evaluator used visual inspection to identify this point in the lift-task. The video was played to this frame in the Dartfish analyzer and the angle drawing tool was used to measure left elbow angle associated with this posture. The left elbow angle was recorded in SPSS for descriptive and statistical analyses.

*Measures*.

Upper Extremity Kinematics.

A summary of angles and positional data obtained from each camera position and data extraction method is provided in Table 4.2 (Frontal Camera position) and Table 4.3 (Sagittal Camera Position). Left elbow (tracked and single frame), left shoulder angle (single frame) and left hand positional co-ordinate data were obtained from the Frontal Camera position; right elbow angle (tracked), right hand positional data and left elbow (single frame) were obtained from the Sagittal Camera position. Head positional data was obtained from both the frontal and sagittal camera positions.

<< Insert Table 4.2 about here >>

<< Insert Table 4.3 about here >>

Relative Head and Hand Movement

Head and hand positional data in isolation were not found to be clinically meaningful consequently, additional analyses was conducted to facilitate interpretation and application of these measures. The difference between participant maximum and minimum vertical head displacement using y-axis coordinate data was calculated to identify head vertical displacement. Head vertical displacement was then normalized to participant height to identify relative head movement. Similarly, the difference between maximum and minimum horizontal hand position was determined and normalized to participant arm length to identify relative horizontal hand displacement. Vertical hand displacement was determined by calculating the difference between maximum and minimum y-positional data; relative vertical hand position was the difference between maximum and minimum normalized to participant height.

All relative positional measures were computed using SPSS v. 20 (Chicago, IL).

## 2.4 Statistical Analyses.

*Reliability*

Intra-rater reliability was assessed for the examiner who conducted all data extraction from Time 1. The examiner repeated all three data extraction methods for each camera position analysis for Time 2 data. When determining Time 2 data from the frontal camera position, the examiner re-established the start and end frames for the tracking data extraction methods and the single frame analyses. Time 2 data from the sagittal camera position was determined using the same start and end frames for the tracking data extraction methods and the single frame analyses. When extracting data from the frontal camera position, the minimum time between Time 1 and Time 2 was 7 days and the average was 30.5 days. The minimum time between Time 1 and Time 2 data extraction from the sagittal camera position was 6 days; the average was 93.9 days. The overall minimum time between Time 1 and Time 2 was 6 days; the overall average was 62.2 days. Participant mean angle and positional coordinates of Time 1 and Time 2 upper extremity and head kinematic data were used for analysis.

Relative estimates of reliability were calculated using intra-class correlation coefficients for absolute agreement ($ICC_{2,1}$)[15]. Reliability coefficients were interpreted according to subjective categories[16] in which 0.4 were considered unacceptable, 0.41 to 0.60 moderate, 0.61 to 0.8 substantial and 0.81 to 1.0 excellent. Standard error of the measure (SEM) and minimal detectable difference (MDC) were calculated as estimates of absolute reliability. SEM, as an estimate of measurement error in angle (degrees) and positional co-ordinate (meters) was calculated using the following formula: $SD_{(average)} \sqrt{1-ICC}$ [17]. $MDC_{90} = SEM \times \sqrt{2} \times 1.65$ [18] was used to measure the amount of change in angle or positional co-ordinates required for an evaluator to be 90% certain the change was beyond the threshold due to measurement error.

**3. Results**

*Demographics*

The firefighter sample (n=12) in this study represented male (n=6) and female active duty firefighters with a mean age of 40.5 (SD = 8.3) years and 11.7 (SD=7.6) years of firefighting service. All participants were right-handed. Gender-specific analysis identified that female firefighters were younger, shorter, weighed less and had few years of service then their male counterparts (Table 4.1). All female firefighters and the majority of male firefighters (67%) held the rank of Firefighter; 33% of male firefighters held the rank of Captain.

*Upper Extremity Kinematics*

Frontal Camera Position:

Descriptive statistics of left elbow angle (tracked and single frame), left shoulder angle (single frame), left hand position (tracked) and head position (tracked) are shown in Table 4.2. The mean left elbow angle using the angle tracking data method (mean of Time 1 and Time 2 means) was 117. 3°. (SD = 12.9°); the mean single frame elbow angle was 78.9° (SD = 32.2°). The mean left shoulder angle (mean of T1 and T2 means) using single frame data extraction was 77.5° (SD = 20.0°). The average relative vertical head displacement was 49.8% (SD = 7.3%) of participant height. The average relative horizontal position of the left hand was 120.5% (SD = 3.7%) of participant arm length and the average relative vertical left hand position was 77.6% (SD = 10.6%) of participant height.

Sagittal Camera Position:

Descriptive statistics of the upper extremity kinematics analyzed from the sagittal camera position are shown in Table 4.3. Using the angle tracking method, mean right elbow angle was 129.0° (SD=17.0°); single frame data analysis determined mean left elbow angle was 89.5° (SD=20.6°). The average relative right horizontal hand position was 131.5% (SD = 29.9%) of participant arm length and relative vertical right hand position was 108.1 % (SD = 9.4%) of participant height. Average relative head vertical displacement was 74.1% (SD=8.6%) of participant height.

*Reliability of Dartfish for Extracting Upper Extremity Kinematics*

Frontal Camera Position:

Table 4.4 shows relative reliability was excellent for single frame shoulder angle ($ICC_{2,1}$ = 0.96) and elbow single frame analysis ($ICC_{2,1}$ = 0.96). Relative reliability was moderate for tracking arm angle ($ICC_{2,1}$ = 0.52). Relative reliability for tracking head vertical position was unacceptable ($ICC_{2,1}$=0.39) but was excellent ($ICC_{2,1}$ = 0.86) for determining relative head displacement. Tracking horizontal (x-coordinate) left hand position was excellent ($ICC_{2,1}$ = 0.94) and was substantial ($ICC_{2,1}$ = 0.64) when tracking vertical (y-coordinate) position. Relative reliability for determining relative left hand position was excellent in both the horizontal ($ICC_{2,1}$= 0.96) and vertical ($ICC_{2,1}$ = 0.92) directions.

As shown in Table 4.4, absolute reliability measured by SEM and $MDC_{90}$ were higher for elbow/arm angle tracking and single frame analysis then shoulder angle single frame analysis. Absolute reliability was lower when determining relative head vertical displacement compared to relative horizontal and vertical hand displacement.

<< Insert Table 4.4 about here >>

Sagittal Camera Position

Table 4.5 shows that relative reliability was substantial for tracking right elbow angle ($ICC_{2,1}$ = 0.67), measuring head ($ICC_{2,1}$ = 0.79) and hand horizontal displacement($ICC_{2,1}$ = 0.74), identifying relative head ($ICC_{2,1}$ = 0.74) and relative horizontal hand ($ICC_{2,1}$ = 0.69) displacement. Relative reliability was excellent for tracking vertical head position ($ICC_{2,1}$= 0.87), tracking hand horizontal ($ICC_{2,1}$ = 0.98) and vertical ($ICC_{2,1}$ = 0.96) positions and using single frame analysis to measure left elbow angle ($ICC_{2,1}$= 0.97).

Table 4.5 demonstrates that absolute reliability was highest for tracking right elbow angle and lowest for determining relative vertical hand position. Absolute reliability was lower for determining relative vertical head and hand displacement than relative horizontal hand displacement.

Tracking elbow angle was the only outcome that consistently demonstrated moderate relative reliability ($ICC_{2,1}$ = 0.52 – 0.67) and high absolute reliability ($MDC_{90}$ = 20.8° – 22.6°) from both the frontal and sagittal camera positions.

<< Insert Table 4.5 about here >>

**4. Discussion**

Overall, our study identified upper extremity kinematics associated with a field-controlled firefighting lift task and provided novel insights into the upper extremity, postural requirements associated with this task. Furthermore, our study demonstrated that upper extremity positional tracking and single frame angle analysis can be reliably extracted using Dartfish from both frontal and sagittal camera positions during this lift task however tracking elbow angle was less reliable than expected.

*Upper Extremity Kinematics*

A paucity of research exists with respect to identifying movement kinematics associated with firefighting tasks. Previous studies have focussed on lower body kinematics[9] and the influence of equipment on balance and postural sway[19,20]. Our findings add to this research as the current study measured upper extremity kinematics during firefighting task performance while simulating firefighting context with selection of a relevant task and use of firefighting equipment. We identified that participants required full range of elbow and shoulder motion during this firefighting lift task which was reflected in hand horizontal position extension beyond anatomical arm length. We suggest this extended reach is a function of the initial position of the high-rise pack, which required participants to reach around the pack to secure its position before lifting to shoulder-level.

Vertical hand displacement measured as a function of participant body height identified that left hand position moved 77% of participant height and right hand position changed 108% of participant height. Furthermore, relative change in right hand horizontal position was higher (131% of arm length) compared to relative change in left hand horizontal position (120% of arm length). These findings in combination provide unique insights into the upper extremity mechanics used by participants to complete this task. For example, right hand position demonstrated overall larger positional excursions compared to the left hand, suggesting that participants relied on the right upper extremity to reach and transfer the HRP more then the left hand. Furthermore, hand position as the distal segment of the upper extremity provides insights into shoulder range of motion. For example, the right hand relative position exceeded participant height (108%), suggesting that participants require full capacity of right shoulder abduction and flexion to facilitate performance of this task.

A methodological challenge of using Dartfish to identify upper extremity kinematics was identified when attempting to measure shoulder range of motion. Upper extremity movements have been identified[21] as challenging to observe due the multiple anatomical planes associated with shoulder movements. Extracting shoulder angle data from the sagittal camera position was particularly challenging as participants initiated the task in a sagittal plane but rotated towards the high-rise pack and subsequently performed the lifting component of the task in a frontal plane of movement. Consequently, identification of a valid measurement of shoulder angle while the participant was facing the sagittal camera was not feasible. A possible solution to the challenge of measuring shoulder angle with Dartfish is to use hand position as a function of body height and / or arm length. We demonstrated that hand position provides a feasible approach to identify shoulder motion requirements associated with task performance. If shoulder angle is necessary, combining data angle extraction from the frontal and sagittal camera positions to identify shoulder range of motion is a possible methodological solution although associated with complexities such as identifying the frame when the shoulder has moved in and out of plane between camera positions. The purpose of this study was to develop reliable data extraction methods using single camera position however further research to develop an approach to extract data using inputs from multiple camera positions is being proposed.

Differences in relative change in vertical head position were observed depending on whether positional co-ordinate data was extracted from frontal or sagittal camera position. Participants moved 50% - 75% of body height in the sagittal plane depending on camera position. Methodological complexities with respect to extracting positional data may contribute to divergent results in relative head position between frontal and sagittal camera position. For example, data extraction from the frontal camera position involved tracking participants' movements through the transverse plane into a sagittal plane of view; data extraction from the sagittal camera position involved tracking participants' movements through the transverse plane into a frontal plane of view. Maintaining the marker position through the transverse plane was challenging, as the data extraction was limited to two dimensions therefore the orientation of the marker needed to change as the participants moved from facing the frontal camera to the sagittal camera and / or vice-versa. Therefore, the initial position of the marker and anatomical landmarks changed as the task progressed. One possible solution is to combine the data extraction from the frontal and sagittal camera and track participants' movements from the frontal camera to the sagittal camera and / or vice versa. This may improve standardization of the marker placement and improve coherence of positional data obtained from both camera positions. Furthermore, optimizing data extraction from both cameras may provide improved insights into the kinematic mechanisms associated with task performance. A primary challenge with this approach will be to identify the frame at which to transfer data extraction between the two cameras. Furthermore, it would have to be determined whether multiple camera positions is beneficial to the quality of information obtained from single camera inputs.

Our results provide initial, preliminary data of firefighting kinematic requirements for a complex, lifting task that is routinely performed during fire suppression activities. We anticipate treatment professionals and ergonomists will be able to use these postural results as a baseline of functional requirements for performing similar firefighting tasks.

For example, our results identifying that firefighters require full elbow motion (180° to 8° flexion) and full shoulder range of motion to perform this task suggest that elbow and shoulder range-of-motion should be maintained to ensure safe, productive performance of this lift task. Furthermore, vertical head displacement can be used to identify potentially awkward postures that may predispose firefighters to injury. Previous research used a 2-dimensional video analysis system to identify changes in spine angles in sewage workers when walking under confined heights[22]. They identified adaptive strategies based on spine kinematics that was used to optimize function during awkward postures. Similarly, our approach to measure vertical head displacement during firefighting tasks might also be used to identify awkward postures and at risk tasks. For example, measuring head displacement during tasks that require crouching to perform work in confined spaces will provide useful information about adaptive strategies used by firefighters with varying individual attributes.

*Relative Reliability*

Relative reliability of upper extremity measures using angle tracking was lower than observed in previous research[10,11,13]. For example, Melton et al.[10] found that found upper extremity angle kinematics could be reliably obtained using Dartfish during overhead reaching. Khadlikar et al.[11] also found that reliable angle tracking measures of the shoulder could be obtained while participants performed activities of daily living ($ICC_{2,1}$ = 0.73 – 0.94). A possible explanation for the difference in relative reliability results is that our study methods using Dartfish differed considerably from this research. Both previous studies used angle tracking to identify shoulder range of motion during reaching and overhead tasks while our study attempted to analyze shoulder movements using angle outputs but methodological challenges previously discussed limited this analysis. Furthermore, both previous studies used controlled, experimental designs including specific skin-based marker placements to facilitate post-data collection analysis; they also limited between subject variability by controlling task performance parameters. In particular, Melton et al.[10] used a highly controlled experimental design to extract glenohumeral angles of healthy and patient participants performing an active and active-assisted overhead shoulder reach. Participants' arm motion was limited to two vertical planes by referring to two black lines on the floor and the scapular plane by positioning participants' feet at a $30^{\circ}$ angle. This protocol reduced the amount of inter-individual variability and resulted in shoulder angles that could be reliably extracted from the sagittal camera position from a single plane of movement (ICC = 0.52 – 0.84)[10]. Our experimental protocol introduced variability between participants performance of tasks as we allowed participants to perform tasks using task mechanics of their individual preference. Furthermore, we did not use skin-based markers but estimated joint center of rotation as participants wore full bunker gear. Although our experimental protocol improved the field-based application of our findings, the variability introduced may have reduced the reliability associated with the angle tracking data extraction method. Consequently, we introduced positional tracking and single frame data extraction methods towards improving both the reliability and methodology of our kinematic analysis approach.

Because of the challenges experienced when tracking shoulder angle we determined that hand position, as the most distal segment of the arm, would provide useful information to characterize the shoulder range of motion necessary to complete this task. For example, if relative hand position indicated that hand position exceeded arm length during the task, this might suggest increased shoulder flexibility would be required to achieve this upper extremity range of motion. Relative vertical hand displacement demonstrated excellent relative reliability from both the frontal/left hand ($ICC_{2,1}$ = 0.92) and sagittal/right hand ($ICC_{2,1}$ = 0.93) camera positions. Our results identified excellent relative reliability for extracting left hand horizontal kinematics from the frontal camera position ($ICC_{2,1}$ = 0.94 – 0.96) and excellent to moderate ($ICC_{2,1}$ = 0.98 - 0.69) reliability when measuring right hand positional kinematics from the sagittal camera position. A possible explanation for this difference in reliability between the two camera positions was that when extracting data from the frontal camera images, participants rotated from a frontal plane to a square position facing the sagittal camera. We were able to observe the hand position through most of the task because the left hand was in view of the frontal camera. However, when analyzing images from the sagittal camera position, we observed that participants rotated from a square position facing the frontal camera to being in plane with frontal camera. This resulted in difficulties observing the right hand position throughout completion of the task. Although the right hand was in view at the start of the task, as participants rotated towards the high-rise pack and positioned themselves in a position to lift the pack, the right hand moved in and out of sagittal camera view, particularly when positioning the hand to initiate the lift and subsequently when manoeuvring the pack to shoulder height. Because the hand moved in and out of view, tracking was suspended during those periods and was re-activated when the hand returned into view. Similar challenges existed when tracking head position ($ICC_{2,1}$ = 0.39 – 0.87). One benefit of using Dartfish is the ability to suspend tracking and correct positional data errors although this may affect outcomes dependent on the spatial data such as velocity[10].

Excellent reliability was observed when using single frame analysis of shoulder and elbow postures from both the frontal camera position ($ICC_{2,1}$ = 0.96) and the sagittal camera position ($ICC_{2,1}$ = 0.97). This approach is similar to using goniometry to assess upper extremity range of motion. Goniometry has been demonstrated to be a reliable method for assessing upper extremity range of motion[23,24]. The advantage of using Dartfish to conduct this analysis is the full suite of analytics can be used to identify a consistent point in the task being performed whereas subjective interpretation of task components is necessary when using goniometry. Furthermore, collecting video images of participants' task performance allows opportunity for additional qualitative analysis post-data collection that may not be possible when using real-time goniometry.

*Absolute Reliability*

Determining the absolute reliability of a movement analysis system is important before applying this approach to identifying the impact of interventions intended to improve or change kinematics associated with a performed task. Absolute reliability, measured by standard error of measurement (SEM) and the minimal detectable change ($MDC_{90}$), identified that reliability was higher when tracking elbow angle than using single frame analysis, from both the frontal and sagittal camera positions. Shoulder angle measured using single frame analysis from the frontal camera position identified higher absolute reliability compared to elbow angle single frame analysis but lower than tracking elbow analysis.

Absolute reliability of relative positional changes in head and hand position identified lower measurement error associated with extracting vertical head position then horizontal hand position. Positional data analysis from the frontal camera position identified that a clinician could be 90% certain that change of 7% in head vertical position and 16% in horizontal hand position would reflect a true change in score and was not an artefact of measurement error. Sagittal camera analysis suggests similar $MDC_{90}$ results for measuring head vertical position (9%) however reliability of horizontal hand position identified a 37% $MDC_{90}$. Overall, absolute reliability results for Dartfish suggest that clinical measurement properties of this movement analysis tool are appropriate.

*Clinical Implications*

Developing reliable tools that can be used in applied contexts to measure kinematics associated with movements or postures has important implications for improving management of worker health. Tools and outcomes can be used to identify opportunities for improving task performance strategies towards improving productivity or that might be associated with injury risk. Ergonomists and employers often collaborate to identify task redesign strategies; subsequently, developing tools that are accessible and feasible for use by ergonomists and employers, is particularly relevant. Our study results suggest that Dartfish supports a reliable movement analysis platform to analyze upper extremity task components from video-based inputs, in an applied context. The following is a summary of our findings and recommendations to facilitate reliable upper extremity data extraction using Dartfish:

1.) Although angle tracking is frequently used in the literature to identify kinematics using Dartfish[6,8,10,11,13], our study results suggest that when identifying upper extremity kinematics associated with a field-controlled task, angle-tracking results in less reliable outcomes compared to other data extraction methods (i.e., positional tracking, single frame analysis).
2.) Extracting positional data is reliable particularly when extracting x-co-ordinate data. Normalizing positional data to a clinically meaningful outcome (i.e., anthropometrics) provides context to the result.
3.) Extracting positional data results in fewer methodological challenges compared to angle tracking (i.e., identifying plane of movement).
4.) Using Dartfish to analyze dynamic movements in applied contexts using the tracking function (angle or positional co-ordinates) results in methodological challenges related to marker obstruction from anatomical segments and objects used in task performance (i.e., high rise pack). We anticipate that our strategy to employ use of the "suspend tracking" function improved the data quality.
5.) Single frame analysis provides a reliable method to extract upper extremity postures associated with task performance.

6.) Using hand positional coordinates relative to arm length (x-coordinate) and body height (y-coordinate) provides useful information about shoulder motion requirements.

*Strength and Limitations*

The primary strength of our study is that we incorporated video imaging, a tool frequently used by ergonomists in assessing occupational tasks[3] and identified a reliable approach to identify upper extremity kinematics, in an applied context. The findings of our research provides preliminary evidence of available methods for translating movement analysis approaches used in controlled, laboratory environments to applied contexts where movement analysis becomes more variable and potentially less stringent. The implications of our findings is that our recommendations can be employed to measure the impact of interventions directed towards improving or changing the way workers perform upper extremity tasks.

The primary study limitation is the participant sample size used for our research although we were able to obtain significant relative reliability outcomes, which we anticipate would be strengthened with larger participant sample sizes. Furthermore, increasing female firefighter participant involvement would increase the power sufficiently to generate sex/gender analysis. This is important for future research directed towards using this approach to understand sex/gender-based differences in task performance including anatomical coupling strategies (i.e., lower versus upper body) and movement variability.

A secondary limitation was our inability to identify an appropriate measurement strategy to identify shoulder movement kinematics associated with this task. Our current study was designed to optimize the methodological analysis associated with extracting kinematic data individually from the frontal and sagittal cameras. We anticipate that incorporating simultaneous analysis of the frontal and sagittal cameras will facilitate analysis of the shoulder. Current research is currently underway to explore this approach and develop an integrative methodology using multiple camera perspectives to analyze multi-planar movements including the shoulder joint.

Our study focussed on intra-rater reliability as previous research has explored and established high inter-rater reliability using Dartfish software for lower extremity analysis[8]. Future research to identify inter-rater reliability of extracting upper extremity movements using our approach (i.e., angle tracking, positional tracking and single frame analysis) is recommended to improve methods using this movement analysis strategy. Furthermore, to identify the translational capacity of this approach, the impact of different raters (i.e., ergonomist versus employer) is recommended.

**5. Conclusions**

We have identified the measurement properties of Dartfish movement analysis software to identify upper extremity kinematics during a field-controlled firefighting lift task. The study findings have implications for using this approach in occupational contexts where identifying upper extremity kinematics is relevant and necessary. The $MDC_{90}$ for tracking was higher (20°) then when using a single frame data extraction approach (15°). Tracking positional data from the frontal camera was associated with the lowest measurement error ($MDC_{90}$ 7%-16% of anatomical segment reference length). Methodological challenges are discussed including marker obstruction and tracking angles through the transverse plane. Recommendations including using positional co-ordinates and developing approaches to use multiple camera angles are provided to address these limitations. Overall, Dartfish provides an accessible, reliable tool to measure upper extremity kinematics in applied contexts.

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## Manuscript Tables

Table 4.1 Participant Demographics

| | Age (years) | Height (m) | Weight (lbs.) | Tenure |
|---|---|---|---|---|
| Male (n=6) | 45 (8.6) | 1.77 (0.12) | 203.8 (12.4) | 16.3 (7.8) |
| Female (n=6) | 36 (5.4) | 1.62 (0.04) | 148.5 (27.7) | 7.0 (3.6) |
| Overall | 40.5 (8.3) | 1.72 (0.10) | 176.2 (35.4) | 11.7 (7.6) |

[ $\overline{X}$ , (SD)]

Table 4.2 Frontal Camera: Upper Extremity Amplitudes

*Hand, Arm, Elbow and Shoulder refer to participants' <u>left</u> side. *Mean and SD represent the mean of the participant mean values. 'Max' is the maximum value of the participant's maximum outcome of the variable of interest and 'min' represents the minimum value in participants' range in the variable of interest*.

| Variable | Time 1 | | Time 2 | |
|---|---|---|---|---|
| | Mean (SD) | Max. / Min. | Mean (SD) | Max. / Min. |
| Arm angle (deg.): Tracked | 119.2 (15.2) | 180.0 / 8.0 | 115.4 (10.4) | 180.0 / 5.4 |
| Head vertical position (m): Tracked | 0.93 (0.09) | 1.58 / 0.50 | 0.92 (0.05) | 1.61 / 0.44 |
| Head vertical displacement (m) | 0.85 (0.10) | 1.00 / 0.71 | 0.86 (0.13) | 1.08 / 0.65 |
| Relative vertical head movement (%) | 49.6 (6.9) | 64 / 39 | 50.0 (8.0) | 62 / 37 |
| Hand position (m): Tracked | | | | |
| Horizontal | 1.90 (0.24) | 2.91 / 1.16 | 1.89 (0.23) | 2.89 / 1.26 |
| Vertical | 1.32 (0.08) | 2.06 / 0.43 | 1.30 (0.15) | 2.10 / 0.39 |
| Hand horizontal displacement (m) | 0.82 (0.20) | 1.20 / 0.58 | 0.83 (0.23) | 1.29 / 0.53 |
| Relative Horizontal Hand Position (%) | 119.8 (30.9) | 178 / 81 | 121.2 (35.8) | 192 / 73 |
| Hand vertical displacement (m) | 1.34 (0.16) | 1.62 / 1.03 | 1.33 (0.15) | 1.54 / 1.04 |
| Relative Vertical Hand Position (%) | 77.8 (11.8) | 104 / 64 | 77.3 (10.4) | 96 / 64 |
| Shoulder angle (deg.): Single Frame | 77.3 (19.8) | 98.4 / 34.9 | 77.8 (21.4) | 108.7/36.9 |
| Elbow angle (deg.): Single Frame | 80.3 (34.3) | 136.3 / 25.5 | 77.4 (31.3) | 122.2/23.1 |

Table 4.3 Sagittal Camera: Upper Extremity Amplitudes
*Hand, Arm refers to participants' right side except for single frame analysis. *Mean and SD represent the mean of the participant mean values. 'Max' is the maximum value of the participant's maximum outcome of the variable of interest and 'min' represents the minimum value in participants' range in the variable of interest.*

| Variable | Time 1 | | Time 2 | |
|---|---|---|---|---|
| | Mean (SD) | Max. / Min. | Mean (SD) | Max. / Min. |
| Arm angle (deg.): Tracked | 127.5 (20.6) | 179.8 / 45.3 | 130.6 (13.2) | 179.6 / 40.7 |
| Head vertical position (m): Tracked | 1.41 (0.24) | 2.49 / 0.48 | 1.46 (0.28) | 2.96 / 0.50 |
| Head vertical displacement (m) | 1.25 (0.13) | 1.52 / 1.00 | 1.31 (0.20) | 1.80 / 0.99 |
| Relative head movement (%) | 72.5 (6.9) | 84 / 62 | 75.8 (10.0) | 97 / 61 |
| Hand position: Tracked<br>Horizontal (m)<br>Vertical (m) | <br>2.59 (0.40)<br>1.82 (0.29) | <br>3.93 / 1.81<br>3.18 / 0.52 | <br>2.60 (0.40)<br>1.80 (0.28) | <br>3.94 / 1.79<br>3.15 / 0.46 |
| Hand horizontal displacement (m) | 0.87 (0.22) | 1.15 / 0.57 | 0.93 (0.21) | 1.29 / 0.70 |
| Relative horizontal hand displacement (%) | 127.2 (31.7) | 169 / 83 | 135.9 (28.7) | 181 / 100 |
| Hand vertical displacement (m) | 1.86 (0.16) | 2.06, 1.56 | 1.86 (0.16) | 2.09 / 1.56 |
| Relative vertical hand displacement (%) | 108.1 (10.0) | 123 / 90 | 108.0 (9.1) | 121 / 90 |
| Lt. Elbow angle (deg.): Single Frame | 91.1 (19.8) | 114.7 / 53.5 | 88.0 (22.4) | 108.9 / 43.3 |

Table 4.4 Frontal Camera: Relative and Absolute Reliabilities of Upper Extremity Amplitudes

| Variable | $ICC_{2,1}$ | 95% CI | SEM | $MDC_{90}$ |
|---|---|---|---|---|
| Arm angle: Tracked | 0.52 | -0.16, 0.83 | 8.9 deg. | 20.8 deg. |
| Head vertical position (tracked) | 0.39 | -0.22, 0.78 | 0.05 m | 0.12 m |
| Head vertical displacement | 0.84 | 0.52, 0.95 | 0.05 m | 0.12 m |
| Relative head movement | 0.86 | 0.59, 0.96 | 3% | 7% |
| Hand Position | | | | |
| Horizontal | 0.94 | 0.79, 0.98 | 0.06 m | 0.14 m |
| Vertical | 0.64 | 0.13, 0.88 | 0.07 m | 0.16 m |
| Hand horizontal displacement | 0.96 | 0.88, 0.99 | 0.04 m | 0.09 m |
| Relative horizontal hand displacement | 0.96 | 0.89, 0.99 | 7% | 16% |
| Hand Vertical Displacement | 0.90 | 0.68, 0.97 | 0.05 m | 0.12 m |
| Relative Vertical hand displacement | 0.92 | 0.76, 0.98 | 3% | 7% |
| Shoulder Angle (single frame) | 0.96 | 0.80, 0.99 | 4.1 deg. | 9.6 deg. |
| Elbow Angle (single frame) | 0.96 | 0.87, 0.99 | 6.6 deg. | 15.4 |

Table 4.5. Sagittal camera: Relative and Absolute Reliabilities of Upper Extremity Amplitudes

| Variable | $ICC_{2,1}$ | 95% CI | SEM | $MDC_{90}$ |
|---|---|---|---|---|
| Elbow/Arm angle: Tracked | 0.67 | 0.19, 0.89 | 9.7 deg. | 22.6 deg. |
| Head vertical position: Tracked | 0.87 | 0.62, 0.96 | 0.09 m | 0.21 m |
| Head vertical displacement | 0.79 | 0.39, 0.94 | 0.07 m | 0.16 m |
| Relative head movement (%) | 0.74 | 0.30, 0.92 | 4% | 9% |
| Hand Position | | | | |
| Horizontal | 0.98 | 0.95, 0.99 | 0.05 m | 0.12 m |
| Vertical | 0.96 | 0.87, 0.99 | 0.05 m | 0.12 m |
| Hand Horizontal displacement | 0.74 | 0.34, 0.92 | 0.11 m | 0.26 m |
| Relative horizontal hand displacement | 0.69 | 0.24, 0.90 | 16% | 37% |
| Hand Vertical displacement | 0.92 | 0.75, 0.98 | 0.04 m | 0.10 m |
| Relative vertical hand displacement | 0.93 | 0.76, 0.98 | 3% | 7% |
| Lt. Elbow Angle (single frame) | 0.97 | 0.84, 0.99 | 3.65 deg. | 8.5 deg. |

**Manuscript Figures**

Figure 4.1: Frontal Camera position

Figure 4.2 Sagittal Camera position

## Chapter Five

**Title: Individual attributes, cardiovascular measures and strength as predictors of firefighters' task performance**

Authors: Kathryn E. Sinden, Joy C. MacDermid, Robert D'Amico, Karen Roche

* Target Journal: Journal of Occupational Rehabilitation

**Abstract.**

Purpose: The aim of this study was to identify the predictive ability of individual attributes, cardiovascular parameters and strength on firefighter task performance time, with implications for developing targeted training programs towards improving firefighter work performance and health.

Methods: Firefighters (n=148), recruited from a south-western Ontario fire service, completed a demographic questionnaire, a hose drag task and a several strength based tasks. Cardiovascular parameters were measured pre- and post-task completion; task performance time was the total time to complete the hose drag task. Descriptive statistics and bivariate correlations were calculated between task completion time and all independent variables. Multiple linear regression models examined the relationship between task completion time and independent variable domains. A final, multi-dimensional model was developed to identify the overall contribution of the significant domain variables on task completion time.

Results: Firefighter participant mean age was 41.9 years (SD=9.6 years); 3% of participants were female. Mean task completion time was 76.7 s (SD=37.2s). Cardiovascular parameters (blood pressure and heart rate) increased between pre- and

post- task completion. Participants' right hand grip strength ($\overline{X}$ =52 kg +/- 11.4kg) was stronger then left hand grip strength ($\overline{X}$ =49.6kg +/- 10.8kg). Average Time 1 NIOSH Lift strength was higher ($\overline{X}$ = 97.9 kg +/- 24.0 kg) than Time 2 ($\overline{X}$ = 92.7 kg +/- 24 kg.). Average NIOSH Lift Maximum strength ($\overline{X}$ = 121 kg +/- 27.2) was higher than either NIOSH Lift (Time 1 or Time 2).

Individual models identified height (t=-2.506, $p$=0.013), pre-task systolic blood pressure (t=-2.576, $p$=0.011) and NIOSH-Lift Maximum (t=2.291, $p$=0.025), significantly predicted task completion time. NIOSH-Lift Maximum was the only independent predictor of task completion time (t=2.291, $p$=0.025) where higher strength was associated with faster task completion time. The final model significantly explained (F[3,67]=4.901, $p$=0.004) 14.2% of variance in task completion time.

<u>Conclusions:</u> Much of firefighter hose drag task performance remains unexplained by the variables examined. As maximum NIOSH lifting as a construct of strength was a significant modifiable factor that contributed to task completion time, some benefit from strength training might be expected on firefighter hose drag task completion time.

**Introduction**

Firefighters perform complex, physically demanding tasks and are exposed to several factors that influence multiple aspects of work health including task performance and injury rates. Previous research has identified that firefighters experience high injury rates; the majority of these injuries are reported as sprains and strains caused by overexertion[1,2]. Furthermore, Liao et al.[3] identified factors that increase injury reporting amongst firefighters and found demographic factors such as age, marital status and gender significantly predict injury severity. These study results provide valuable contributions to understanding firefighter injury characteristics, however, understanding how these same factors impact task performance with a view on injury prevention would provide critical insights into the components necessary for developing effective injury prevention strategies.

Developing injury prevention strategies requires identification of relevant aspects of task performance that require modification or specific training. Injury prevention strategies might include modifications to the way the task is performed or development of training programs that target individual modifiable attributes such as strength and endurance associated with improving task performance. For example, recent research[4–7] has focussed on understanding the interrelationship between physical fitness and firefighter task performance time with the goal of developing training programs that target specific components of firefighter job tasks. Task performance time is often selected as the outcome of interest in firefighting, as emergency response tasks are often performed under time restraints due to urgency associated within the occupational context. This research has provided valuable insights into the relationship between exercises such as bench press and isokinetic movements as strength indicators and predictors of job performance. A primary limitation with these studies is the selected strength activities correlated with task performance fail to replicate the complexity of firefighting tasks. Furthermore, the context of the fire service including demographics and training approaches may impact task performance outcomes.

In addition to strength demands, firefighting places great demands on the cardiovascular system. Studies have evaluated cardiovascular demands related to firefighting tasks through measuring aerobic and anaerobic capacity associated with simulated firefighting tasks[8,9]. A primary limitation of this research is that evaluating aerobic and anaerobic cardiovascular capacity is complex and may not provide an accessible method for firefighters and / or clinicians who wish to monitor cardiovascular outputs associated with firefighting. A recent systematic review[10] identified factors that predispose firefighters to increased risk of cardiovascular disease (CVD) and acknowledged the well-documented physical and environmental factors resulting in high demands placed on firefighters' cardiovascular system. However the study also revealed that firefighters are susceptible to risk factors prevalent in the general population including low fitness, obesity and other common CVD risk factors such as hypertension. These factors might compound the impact of physical demands and further increase the prevalence of CVD. Although research has measured cardiovascular capacity related to firefighting[9,11], understanding the relationship between parameters associated with both cardiovascular capacity and general health such as blood pressure, will provide insights into how general health status impacts task performance with implications for injury prevention and wellness management.

Determining the influence of individual attributes such as age, gender, height, weight and years of service on firefighting mechanics is also anticipated to improve the efficacy of firefighter injury prevention programs. Developing a multi-level model that considers the relative predictive ability of demographic characteristics, strength and cardiovascular parameters of health on firefighter task performance will provide unique insights into developing a comprehensive firefighter injury prevention strategy. Consequently, the overall purpose of this study was to determine which individual and performance based variables are most predictive of firefighter task completion time as an indicator of job performance. Specifically, the primary objectives of this study were to determine: (1) the predictive ability of demographic factors alone on hose drag task completion time (2) the ability of cardiovascular parameters such as heart rate and blood pressure to predict task performance time (3) the ability of functional strength measures to predict hose drag completion time and (4) a multi-level model predictive of hose drag performance time.

**Methods**

This is a cross-sectional analysis of data collected in the first phase of an ongoing prospective cohort study (FIRE-Well), which is aimed to identify predictors of firefighter work health. Study participants (n=148) were active-duty firefighters recruited from a South-western Ontario fire service consisting of 471 active-duty firefighters. The study protocol was approved by Hamilton Integrated Research Ethics Board at McMaster

University. All participants provided written, informed consent prior to study enrolment. Data for the current study was collected from January 2012 to March 2012.

**Data Collection**

Firefighter study participants completed a questionnaire reporting demographic characteristics. Firefighter participants also completed a static NIOSH-Floor lifting protocol using the J-Tech Freedom® Wireless Static Force Gauge and a hose drag task. All study components were completed in the firefighters training facility in Hamilton, Ontario. Access to the training facility allowed access to bona-fide firefighting equipment and permitted firefighters to perform the hose drag task in full firefighting bunker gear (22.7 kg) plus self-contained breathing apparatus (SCBA) (18.1 kg.), improving simulation of an actual fire-suppression context.

*Hose Drag Task*

The hose drag component of fire suppression activities has been identified by this cohort of firefighters as physically demanding due to challenges with manoeuvring the hose around physical barriers and the additional physical forces required to lift and pull a "charged" hose. The study protocol design was limited to using an uncharged hose however a barrier was used to improve simulation during actual fire suppression.

A designated start / finish line was established from which the task was initiated and terminated. Study participants initiated the task in standing at a designated start / finish position. When instructed to begin, the firefighters bent to floor level and lifted the nozzle (6.1 kg.) of an uncharged firefighting hose (30 m). The firefighters were given standardized instructions to pull the uncharged fire hose a distance of 18 m to a pylon.

Once at the pylon, the firefighters manoeuvred the hose around the pylon and pulled the hose to an end marker positioned 12m from the pylon. The firefighters then reversed the task components to return the nozzle to the start / finish line. Participants were timed while performing the task; blood pressure (systolic and diastolic) and heart rate were measured and recorded pre and post task completion.

*Measures*

a) Task Completion Time.

The outcome of interest in this study was task completion time measured with a Sportline K256 stopwatch while participants performed the hose drag task and was measured as the total amount of time required performing the task. Task completion time has been used in previous research[4,6,7] as an indication of firefighter performance as emergency response activities are time sensitive. Time was started when firefighters initiated a forward, downward reach to obtain the nozzle of the hose and time was stopped when firefighters crossed the designated start / finish line. Task completion time was recorded in seconds where superior performance was reflected in lower task completion times.

b) Individual Attributes.

Individual attributes have been associated with firefighter injury rates[3] and with task performance outcomes[6]. A questionnaire was administered prior to completing the hose drag task and / or the strength testing. The questionnaire requested reporting of age, sex/gender, height and years of service. Weight was measured using a standard weigh scale (AMG Professional Hydraulic Scale).

c) Cardiovascular Measures.

Aerobic capacity and fitness levels have been identified to impact exercise performance and task performance amongst firefighters[9,11–13]. Blood pressure and heart rate were obtained to monitor participant cardiovascular response to task completion. Measurements were obtained pre- and post-task using an automated blood pressure monitor (OMRON 7 Series, BP760Can, Intellisense). Blood pressure was administered on participants' non-dominant arm and recorded in mmHG.

d) Strength Measures.

Strength has been identified as predictive of ability on several fitness and simulated firefighting tasks[4]. Furthermore, our previous research has identified strength as a focus amongst female firefighters towards maintaining job performance[14]. A series of strength measures were obtained including grip strength and static lift capacity. Grip strength measurements were obtained using a JAMAR grip strength dynamometer. Grip strength was administered on participants' dominant and non-dominant sides, prior to completing the hose drag task. Standard grip strength protocol was followed where participants assumed a sitting position, the "grip" bar of the JAMAR was set at position 2 and / or adjusted such that the bar rested comfortably at the metacarpophalangeal joint; participants' elbow was non-supported and positioned at 90° angle. Participants were asked to exert a maximum grip force. The maximum grip strength generated was recorded.

Static lift measures were obtained and recorded automatically using the J-Tech Freedom® Wireless Static Force Gauge and administration of the NIOSH Floor lift protocol. The static NIOSH-Floor lift protocol was selected as it reflected mechanics similar to those used when retrieving the hose at task initiation. The NIOSH-Floor lift protocol required participants to stand with their feet shoulder-width apart and 25 cm horizontally from the center of the attachment for the lifting handle. The lift handles were set 15 cm vertically from the top of the lift platform. Participants were required to bend and grasp the lifting handles that were attached to the force gauge and sustain a static lift while in that posture for 10 seconds. A second trial was performed following a 30 second rest break. A practice trial was provided to allow participants to become familiar with the static lift mechanics and posture. Standardized instructions were provided to each participant. The individual mean lift capacity of trial 1 and trial 2 were recorded in addition to the high mean result and the maximum lifting capacity from all trials.

NIOSH Lift Time 1 and Time 2 represent the average force exerted from the start to the end of the test. NIOSH Lift High Mean is the highest mean force from the two repetitions and NIOSH Lift Maximum is the maximum lift force generated between the two repetitions. The NIOSH lift protocol was conducted with half of the study sample as it was introduced into the FIRE-Well research study after study initiation when all research stakeholders agreed to its inclusion.

**Statistical Analysis**

Descriptive statistics were calculated for hose drag task performance time and for all independent variables. Bivariate correlations between task completion time and all independent variables were determined. Multiple linear regression examined the relationship between hose drag task completion time (dependent variable) and individual attributes, cardiovascular and strength variables. Models were created separately for each variable set (individual attributes, cardiovascular and strength) to determine contribution of individual predictors to task completion time. As our previous research[15] has demonstrated age and gender effects on task performance, we included these variables as covariates in each model. Each independent variable was evaluated with respect to its predictive ability above that offered by the other included independent variables. To determine the overall contribution of the identified variables computed from the conceptual regression models on task completion time, a final model was created using a backward stepwise approach with those identified significant predictors ($p < .05$). Regression diagnostics and analysis of predicted to residual regression values were conducted to determine any violations of normality, non-multicollinearity, and homeoscedasticity (Appendix E). All analyses were conducted using SPSS v. 20 (IBM SPSS, Chicago, IL).

**Results.**

*Descriptive Statistics*

A total of 148 participants were included in the study; 71 (48%) of participants completed the NIOSH lifting protocol. 3.4% of study participants were female which is representative of female firefighters in firefighting[16]. The mean age was 41.9 +/- 9.6 years; gender-specific comparisons indicate the female firefighters were younger, smaller and had experienced fewer years of service ($\bar{X}$ = 5.1 years, +/- 3.5 years) than the male firefighters ($\bar{X}$ = 14.0 years +/- 9.9 years) (Table 5.1).

<< Insert Table 5.1 about here >>

As shown in Table 5.2, the mean task completion time was $\bar{X}$ = 76.7 s +/- 37.2 s seconds; the range was 20.4 - 95.0 seconds (74.6 seconds). The average blood pressure prior to task completion was 139/86 mmHG; post task blood pressure was 167/91 mmHG. Corresponding mean heart rate was 68 bpm pre-task and 99 bpm post-task. On average, participants' demonstrated higher right hand grip strength ($\bar{X}$ = 52 kg., SD = 11.4 kg.) when compared to their left hand ($\bar{X}$ = 49.6 kg SD=10.8 kg.) Furthermore, participants demonstrated higher mean lift force during Time 1 ($\bar{X}$ = 97.9 kg. SD=24.0 kg.) in comparison to Time 2 ($\bar{X}$ =92.7 kg. SD=24.) during the static NIOSH-Floor lift protocol. As anticipated, the average maximum lift force generated was higher than either Time 1 or Time 2.

<< Insert Table 5.2 about here >>

*Bivariate Correlations*

Table 5.3 presents the results of the bivariate correlations between the predictor variables within each of the three conceptual model frameworks and task completion time. Age ($r$=0.34), years of service ($r$=0.32) and NIOSH Lift Maximum ($r$=-0.32) showed significant correlations ($p$<.01) with task completion time; systolic blood pressure (pre) ($r$=0.12), NIOSH Lift High-Mean ($r$= -0.19)were significant with task completion time at $p$<.05. Age ($r$ = 0.34), years of service ($r$ = 0.32) and NIOSH Lift Maximum ($r$ = -0.32) demonstrated moderate[17] correlation with task performance; Systolic Blood Pressure (post) showed a large correlation with task performance time ($r$ = -0.83)[17].

<< Insert Table 5.3 about here >>

*Regression*

Individual simple regression models were developed to identify variables predictive of task performance time corresponding to each conceptual category: individual attributes, cardiovascular and strength (Table 5.4). Age and gender were entered into all models as covariates of task performance time. The variables included in the individual attributes model were: height, weight, gender. Tenure was not included in the model due to collinearity with age. This model accounted for 13% of the variability of task completion time; height was the only significant unique predictor of task completion time explaining 3.7% of the variance (Table 5.5).

<< Insert Table 5.4 about here >>

<< Insert Table 5.5 about here >>

The cardiovascular measures model included systolic and diastolic blood pressure (pre and post), and heart rate (pre and post). The full cardiovascular model accounted for 15.2% of the variance in hose drag time; systolic blood pressure-pre was the only significant unique predictor of task completion time explaining 3.9% of the variance (Table 5.6).

<< Insert Table 5.6 about here >>

The variables included in the Strength regression model were grip strength (right and left), NIOSH lift (Time 1 and Time 2), NIOSH – High Mean and NIOSH – Max. Collinearity was observed with NIOSH-Time 2 and NIOSH-High Mean. Because the High-Mean represented the highest mean between NIOSH Time 1 and Time 2, the High-Mean score was removed from the Functional Strength model to allow representation of both trials. This adjustment reduced the collinearity to acceptable tolerance and VIF levels. Although the model overall was significant, no independent variables independently contributed to hose drag performance time. Based on low beta coefficients and significance levels, grip strength (left) and NIOSH (T1) were removed stepwise from the model. The final Strength model included NIOSH Lift Maximum, NIOSH Lift Time 2 and Grip Strength-Right, controlling for age and gender. This final model accounted for 14.8% of the variability in hose drag task completion performance time and NIOSH-Lift Maximum was the only significant unique strength predictor of task completion time accounting for 8.5% of the variance (Table 5.7).

<< Insert Table 5.7 about here >>

To identify how the three constructs, demographic characteristics, cardiovascular and strength, contribute to task performance time, a multi-dimensional model was developed to identify the individual contributions of each construct. A full model was developed including the significant individual predictors from each of the three constructs; Height, Systolic Blood Pressure (pre-task) and NIOSH-lift Maximum (Table 5.8). Although the overall model was significant ($p$=0.007) and explained 15% of the variance in task completion time, no predictor variable contributed independently. To clarify the relationship between these three conceptual models and task completion time, a stepwise approach was used to remove variables based on lowest beta coefficients and significance. Height was first removed then pre-task systolic blood pressure. The final model (Table 5.9) accounted for 14.3% of the variance in task performance time and NIOSH-Lift Maximum uniquely explained 6.4% of variance.

<< Insert Table 5.8 about here >>
<< Insert Table 5.9 about here >>

**Discussion**

Firefighting provides a unique context to study how individual factors impact task performance in a physically demanding, male dominant occupational culture. Results from understanding the interrelationship between the individual and task performance outcomes will facilitate development of contextualized training programs designed to target modifiable constructs within these factors. Our study identified that height, pre-task systolic blood pressure and NIOSH-Lift Maximum were the strongest predictors of task completion time when modelled independently. When entered into a multi-dimensional model that incorporated the significant predictors from each of the three domains, the three constructs together significantly explained 15.1% ($p$=0.007) of the variance in task completion time however none of the variables independently contributed to the model. NIOSH-Lift Maximum significantly contributed 6.4% ($p$=0.025) of the variance only when height and pre-task systolic blood pressure were removed from the model. Although the final model containing only NIOSH-Lift maximum was significant, it accounted for only 14.3% ($p$=0.004) of task completion time variance. Because of the robust effect of increasing age on decreased task performance and workplace injuries, it was retained in all models. Although gender did not impact task performance time, gender specific effects have been observed on firefighting task performance[14,15,18,19] and was also retained in all models to account for the known effects of gender in firefighting task performance. However given the small sample size of female firefighters, we were unable to identify gender effects or stratify analysis based on gender.

*Demographic Characteristics*

The present study identified that personal attributes including age, height, weight and gender significantly accounted for only 13% variance in task performance time suggesting it would be difficult to accurately predict firefighter task performance time based on these demographic variables alone. However, when considering independent variable contributions, age (t=4.190, $p<0.01$) and height (t= -2.506, $p=0.013$) were found to be significantly predictive of task completion time where increasing height was associated with faster task performance times and increasing age was associated with slower task performance times. In a study that considered the relationship between physical fitness measures and task performance time during a series of firefighting tasks, Michaelides et al.[7] also identified a significant, moderate correlation between increasing aging and slower task performance time. To further clarify the effect of age on task performance time, the same study[7] categorized participants into two groups based on task performance time; "best performers" were participants who completed the task protocol in less than 5 minutes and the "poorest performers" required more than 9 minutes to complete the protocol. Their results identified an age effect on task performance time where the average age of the best performers was 26 years +/- 3 years and the poorest performers were 38 years +/- 8 years. Although biophysical aspects associated with age and firefighting were not identified in either the current or previous study[6], biological changes related to aging, physiology and the musculoskeletal (MSK) system have been previously discussed[20–22]. Furthermore, a comprehensive approach that addresses the physiological aspects related to aging has been suggested to maintain work ability[23]. That age alone represents such a strong predictor of task performance in the current and previous study, and that age is a relevant with respect to biophysical aspects of MSK health, suggests that individualized training programs focussed on addressing modifiable performance-based factors associated with an aging population in firefighting may be warranted.

Although we did not identify a significant correlation between task completion time and height, our regression model with personal attributes identified height as a significant predictor of task performance time ($t=-2.506$, $p=0.013$) where taller firefighters were able to perform the drag task in less time than shorter individuals. Few studies have considered the impact of height on task performance although studies have identified body mass index (BMI), a measure of body weight normalized to height, as a negative correlate of task performance[7,10]. A longer stride length is associated with increasing height, which may be important when completing this hose drag task therefore the height advantage in firefighting may be task dependent. That height did not remain in our final model, suggests that height may be an unstable independent predictor of firefighter task performance, especially when the effects are small.

*Physiological Characteristics*

When considering variables in the physiological model, pre-task systolic blood pressure was found to significantly predict task completion time ($t=-2.576$, $p=0.011$) even when controlling for age. Furthermore, pre-task systolic blood pressure was the only variable that demonstrated a large correlation[17] with task completion time ($r = -0.83$, $p =$

0.32), where higher pre-task systolic blood pressure was associated with faster task completion times.

The importance of considering the impact of blood pressure on task completion time is supported by a recent systematic review, which identified that 50% of firefighters have been diagnosed with hypertension, a modifiable risk factor for cardiovascular (CV) disease[10]. The majority of CV events occur in persons with mild hypertension, defined by systolic blood pressure range of 140 – 146 mm HG and diastolic blood pressure range of 88 – 92 mm Hg[24]. Although blood pressure and heart rate provide accessible methods to evaluate CV health, previous research has focussed on determining aerobic[9,25] and anaerobic[8] capacity in firefighters. Measuring an/aerobic capacities certainly provides valuable information about firefighter's cardiovascular capacity with the expectation that increased cardiovascular capacity will result in better task performance, however there is uncertainty in the literature about the minimum required aerobic capacity to enable safe work amongst firefighters. Furthermore, the process of obtaining outputs associated with aerobic and anaerobic capacity can be complex and time consuming. Evaluating firefighter cardiovascular response during firefighting tasks with particular focus on less operationally complex measures of heart rate and blood pressure provides an alternative, accessible method of measuring CV health.

Our approach to evaluate pre- and post-task heart rate and blood pressure provided unique insights into CV response during this task. The average pre-task blood pressure was 139/86 mm HG trending towards mild hypertension but was similar to the resting blood pressure (134/87 mm HG) observed in Michaelides et al.[7]. Although these results suggest this cohort of firefighters are at risk for CVD due to elevated blood pressure, elevated pre-task blood pressure was predictive of improved task performance even when controlling for age. This relationship between elevated systolic blood pressure and task performance is unclear; it may be that elevated systolic blood pressure acts as a physiological primer to improve task performance or that the effects of systolic blood pressure on task performance are mediated by an interaction, which may be explored with a larger sample size. Regardless, pre-task systolic blood pressure was not independently predictive of task performance time when included in the multi-dimensional model, suggesting that although blood pressure has important health and performance implications, it may not be the most important predictor of strength-related tasks (i.e., hose drag).

*Strength*

An increasing body of literature[4–7] has positioned to identify the relationship between physical strength measures and firefighter task performance with implications to evaluate firefighter work capacity and to inform training programs that will directly translate to firefighter task performance. For example, Rhea et al.[4] examined correlates between strength and job performance. Job performance was measured by task completion time on a series of tasks including hose pull, stair climb with a high-rise pack, simulated victim drag and equipment hoist. Strength was measured during a 5-repetition maximum flat bench press and squat and handgrip. Their results found high correlations between both handgrip ($r$ = -0.85) and bench press ($r$ = -0.80) and task performance time during a hose drag task. Furthermore, previous research has consistently identified a robust relationship between grip strength and task performance time amongst firefighters[4,5,7]. Conversely, our results demonstrated a low correlation between handgrip and hose drag ($r$ = -0.16) and moderate relationship between maximum static floor lift (NIOSH) ($r$ = -0.32) and hose drag task performance time where higher strength was associated with faster task completion time. Further exploration of our study results with respect to handgrip identified lower and more variable right hand grip strength compared to the other studies[4,5,7]. This difference may be attributed to an age differential between our cohort of firefighters ($\overline{X}$ = =41.9 years +/- 9.6 years), and the younger cohorts studied (mean age range 33 years – 39 years). Furthermore, we conducted our grip strength in a sitting position compared to Lindberg et al[5] who conducted their grip strength protocol in a standing position. Both age and procedural differences may contribute to the variable handgrip strength results observed in our study.

Previous research exploring the relationship between strength and firefighter work capacity often used functional, fitness-based tests such as bicep curls, shoulder press, bench press, push-ups, situps which were found to be associated with various firefighting tasks (i.e., hose drag, victim rescue, stair climbing)[4,5,26]. Our study used a similar approach to identify strength using a static lift NIOSH-Floor lift protocol. This specific protocol was selected to reflect the frequent bending and lifting postures associated with firefighting tasks[13,27]. Once issues with multicollinearity were addressed in the strength model, NIOSH-Lift maximum was the strongest independent predictor of task performance time (t=2.291, $p$=0.025) where higher force output (i.e., strength) was associated with faster task completion time. However, when entered into a multi-dimensional model with height and pre-task systolic blood pressure, strength was no longer a significant predictor of task performance suggesting the effect of strength on task performance time might be moderated by height and pre-task systolic blood pressure. Our results are similar to Lindberg et al.[5] who found maximum handgrip strength, bench press, chin ups and upright barbell row significantly correlated with firefighter work capacity. Furthermore, Rhea et al[4] also considered the effect of different fitness domains on hose drag task performance and found the strongest correlations between strength composite measures and hose drag completion time. Consequently, further research and interventions directed towards improving firefighter strength to affect job performance and improve ancillary health outcomes (i.e., blood pressure) is warranted.

*Limitations*

The primary limitation in the current study is the variables selected proved to make a less substantial contribution to explaining task performance time than anticipated and hence were somewhat unstable given our sample size. There were issues with multicollinearity, which were addressed by a series of decisions regarding the inclusion of variables in the models. The underrepresentation of female firefighters limited our ability to detect gender effects. Further, given our sample size, we were unable to test for interactions and our results suggest this might have been useful. The task we modeled simulated dragging a hose during emergency response however, the hose was not charged (filled with water) and was not associated with stressors associated with an actual emergency response situation and hence may not replicate the physiological responses (i.e., heart rate, blood pressure) associated with the occupational context. Finally, our sample was from one fire service and there may be variations in demographic characteristics, training and task performance across different contexts.

**Conclusions**

Our study evaluated the predictive ability of performance-based outcomes on firefighter task completion time during a hose drag task. It was determined that independently, increasing height, pre-task systolic blood pressure and NIOSH-Floor lift strength were associated with improved task completion time. When combined in a multi-dimensional model, NIOSH-Floor lift was the only predictor of task performance time, independent of height and pre-task systolic blood pressure. Our results support previous research[4,5,7] and suggest that firefighting training programs focussed on improving job performance, would benefit from focus on strength training.

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Table 5.1 Demographic Characteristics, Mean (SD)

| | n (%) | Age (years) | Height (inches) | Weight (lbs) | Tenure (years) |
|---|---|---|---|---|---|
| Male | 143 (96.6) | 42.1 (9.6) | 71.0 (2.7) | 204.5 (26.8) | 14.0 (9.9) |
| Female | 5 (3.4) | 34.2 (6.9) | 65.8 (1.8) | 144.5 (17.3) | 5.1 (3.5) |
| Total | 148 (100) | 41.9 (9.6) | 70.9 (2.9) | 202.5 (28.6) | 13.7 (9.9) |

Table 5.2 Descriptive statistics of task completion time and predictor variables.

| | Mean (SD) | n (%) |
|---|---|---|
| Task Completion Time (sec.) | 76.7 (37.2) | 146 (98) |
| **Cardiovascular Parameters** | | |
| Blood Pressure – Pre (mmHG) | | |
| Systolic | 139.1 (15.1) | 148 (100) |
| Diastolic | 86.2 (10.3) | 148 (100) |
| Blood Pressure – Post (mmHG) | | |
| Systolic | 166.8 (21.3) | 147 (99.3) |
| Diastolic | 91.0 (14.2) | 147 (99.3) |
| Heart Rate (bpm) | | |
| Pre- | 68.1 (12.2) | 148 (100) |
| Post- | 99.4 (18.4) | 147 (99.3) |
| **Strength Parameters** | | |
| Grip Strength (kg.) | | |
| Right | 51.5 (11.4) | 147 (99.3) |
| Left | 49.6 (10.8) | 147 (99.3) |
| NIOSH Lift (kg.) | | |
| Time 1 | 97.9 (24.0) | 71 (48.0) |
| Time 2 | 92.7 (24.0) | 71 (48.0) |
| High Mean | 101.2 (23.5) | 71 (48.0) |
| Maximum | 121.3 (27.2) | 71 (48.0) |

Table 5.3. Correlations between Predictor Variables and Task Performance Time

| | Pearson r | P Value |
|---|---|---|
| **Demographic variables** | | |
| Age | 0.34 | < 0.001 |
| Height | -0.16 | 0.06 |
| Weight | 0.01 | 0.93 |
| Gender | -0.07 | 0.39 |
| Tenure | 0.32 | < 0.001 |
| **Cardiovascular Parameters** | | |
| Blood Pressure – Pre (mmHG) | | |
| Systolic | -0.19 | 0.02 |
| Diastolic | 0.04 | 0.66 |
| Blood Pressure – Post (mmHG) | | |
| Systolic | -0.83 | 0.32 |
| Diastolic | 0.05 | 0.54 |
| Heart Rate (bpm) | | |
| Pre- | 0.12 | 0.20 |
| Post- | 0.05 | 0.56 |
| **Strength Parameters** | | |
| Grip Strength (kg.) | | |
| Right | -0.16 | 0.05 |
| Left | -0.16 | 0.05 |
| NIOSH Lift (kg.) | | |
| Time 1 | -0.24 | 0.04 |
| Time 2 | -0.13 | 0.35 |
| High Mean | -0.27 | 0.02 |
| Maximum | -0.32 | < 0.01 |

Table 5.4. Demographic, Physiological, Strength Constructs and Task Completion Time (model summaries)

| Model | R | $R^2$ | Adj. $R^2$ | Std. Error of the Estimate | Change Statistics | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | $R^2$ Change | F Change | Df1 | Df2 | Sig. F Change |
| 1 | 0.392[a] | 0.154 | 0.130 | 13.49704 | 0.154 | 6.460 | 4 | 142 | 0.001 |
| 2 | 0.445[b] | 0.198 | 0.152 | 13.32906 | 0.198 | 4.240 | 8 | 137 | 0.001 |
| 3 | 0.458[c] | 0.210 | 0.148 | 13.35731 | 0.210 | 3.398 | 5 | 64 | 0.009 |

Dependent Variable: Task completion time (sec)
a Predictors: (Constant), Age, Gender, Weight, Height
b Predictors: (Constant), Age, Gender, Systolic Blood Pressure (Pre, Post), Diastolic Blood Pressure (Pre, Post)
c Predictors: (Constant), Age, Gender, Grip Strength (right), NIOSH (T2), NIOSH-Max

Table 5.5 Demographic Variables and Task Completion Time (coefficients)

| Model | Unstandardized Coefficients | | Standardized Coefficients | t | Sig. |
|---|---|---|---|---|---|
| | B | Std. Error | Beta | | |
| Constant | 109.091 | 33.376 | | 3.268 | 0.001 |
| Age | 0.492 | 0.117 | 0.327 | 4.190 | 0.000 |
| Gender | -5.659 | 6.783 | -0.071 | -0.834 | 0.406 |
| Weight | -1.208 | 0.482 | -0.239 | 0.976 | 0.331 |
| Height | 0.048 | 0.049 | 0.095 | -2.506 | 0.013 |

Table 5.6 Physiological Variables and Task Completion Time (coefficients)

| Model | Unstandardized Coefficients | | Standardized Coefficients | t | Sig. |
|---|---|---|---|---|---|
| | B | Std. Error | Beta | | |
| Constant | 59.641 | 16.280 | | 3.664 | 0.001 |
| Age | 0.523 | 0.122 | 0.348 | 4.307 | 0.001 |
| Gender | -8.543 | 6.479 | -0.107 | -1.318 | 0.190 |
| Heart Rate (pre) | 0.194 | 0.128 | 0.163 | 1.512 | 0.133 |
| Heart Rate (post) | -0.042 | 0.081 | -0.054 | -0.523 | 0.602 |
| Blood Pressure – Systolic (pre) | -0.239 | 0.093 | -0.249 | -2.576 | 0.011 |
| Blood Pressure – Systolic (post) | -0.060 | 0.061 | -0.088 | -0.979 | 0.329 |
| Blood Pressure – Diastolic (pre) | 0.051 | 0.144 | 0.036 | 0.356 | 0.723 |
| Blood Pressure – Diastolic (post) | 0.056 | 0.088 | 0.055 | 0.636 | 0.526 |

Table 5.7 Functional Strength Variables and Task Performance Time (coefficients)

| Model | Unstandardized Coefficients | | Standardized Coefficients | t | Sig. |
|---|---|---|---|---|---|
| | B | Std. Error | Beta | | |
| Constant | 53.836 | 18.892 | | 2.850 | 0.006 |
| Age | 0.389 | 0.179 | 0.258 | 2.175 | 0.033 |
| Gender | -8.254 | 9.385 | -0.103 | -0.879 | 0.382 |
| Grip strength (right) | 0.077 | 0.176 | 0.060 | 0.437 | 0.663 |
| T2 NIOSH lift | 0.143 | 0.096 | 0.237 | 1.487 | 0.142 |
| Max – NIOSH lift | -0.254 | 0.096 | -0.477 | -2.631 | 0.011 |

Table 5.8. Final Model with significant predictor variables from each of the conceptual models

| Model | R | $R^2$ | Adj. $R^2$ | Std. Error of the Estimate | Change Statistics | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | $R^2$ Change | F Change | Df1 | Df2 | Sig. F Change |
| 1 | 0.460[a] | 0.212 | 0.151 | 13.33275 | 0.212 | 3.493 | 5 | 65 | 0.007 |
| 2 | 0.449[b] | 0.202 | 0.154 | 13.31346 | 0.202 | 4.176 | 4 | 66 | 0.004 |
| 3 | 0.424[c] | 0.180 | 0.143 | 13.39498 | 0.180 | 4.901 | 3 | 67 | 0.004 |

Dependent Variable: Task Completion Time (sec)
a (Constant), Age, Gender, Height, Systolic Blood Pressure (pre), NIOSH – Max
b (Constant), Age, Gender, Systolic Blood Pressure (pre), NIOSH-Max
c (Constant), Age, Gender, NIOSH-Max

Table 5.9. Final Model with NIOSH-Max as significant predictor or task completion time (coefficients)

| Model | Unstandardized Coefficients | | Standardized Coefficients | t | Sig. |
|---|---|---|---|---|---|
| | B | Std. Error | Beta | | |
| Constant | 57.719 | 17.625 | | 3.275 | 0.002 |
| Age | 0.383 | 0.176 | 0.255 | 2.175 | 0.033 |
| Gender | -7.917 | 9.260 | -0.099 | -0.855 | 0.396 |
| NIOSH-Max | -0.145 | 0.063 | -0.273 | 2.291 | 0.025 |

## Chapter Six:

**The Evolution of FIRE-WELL: Improving Firefighters' Health through Research and Partnership**

Authors: Kathryn Sinden and Joy MacDermid



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### Introduction

Firefighters provide an essential service within our communities; they respond to emergency situations and ensure our neighbourhoods are safe. The intersecting and cumulative effects of the cardiovascular, physical and emotional demands of firefighting, have been linked to high rates of injury[1], with musculoskeletal disorders (MSD) accounting for one-third of all injuries[2]. Although female firefighters represent only 3% of all firefighters[3], the number of female firefighters is increasing and they experience elevated risks of injury compared to their male counterparts[4]. Firefighters and their municipal employers are challenged to support optimum health given the complex physical and psychological challenges associated with firefighting.

The Knowledge-to-Action (KTA) process model[5] is a theoretical framework based on synthesis of multiple planned action theories and has guided our program of research with the firefighters. One of guiding the tenets of the KTA is that evidence about effective musculoskeletal injury prevention needs to be contextualized to this unique occupational context to ensure that the outcomes are relevant. To date, there has been little translational work directed towards injury management programs for firefighters. For example, it is not known what musculoskeletal tests or screening processes, might detect MSD in firefighters. The following story tells of the evolving participatory research and knowledge translation (KT) partnership between researchers and firefighters focused on development of FIRE-Well, an evidence-based injury management program. This case emphasizes the barriers and facilitators to KT within this complex occupational context (see Figure 6.1).

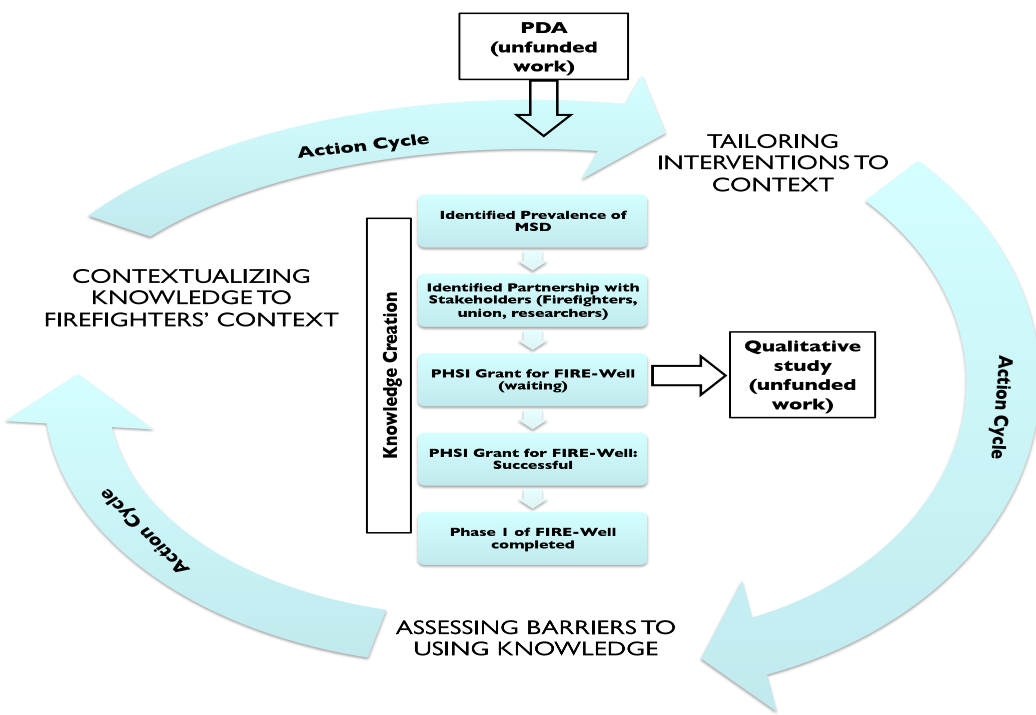


**Figure 6.1. Schematic of Knowledge Translation Partnership.**
The internal process flow chart demonstrates the sequence of activities during the phase of developing the knowledge creation partnership from identification of the problem, through design of the project and grant to implementation of the first phase of FIRE-Well. The outside cycle represents the action cycle as existing and project knowledge[5] are contextualized and applied to the firefighter context.

**Building partnerships to build success**

Developing effective partnerships between occupational stakeholders and researchers can be difficult, but is critical when identifying effective KT strategies. Active engagement of occupational groups during the initial phases of research is known to ensure the identified methods and outcomes are contextually relevant[6]. The development and implementation of the FIRE-Well project was led by firefighter research partners as full co-principal investigators as is essential to effective KT.

For instance, one of the early projects undertaken during the evolution of FIRE-Well was the development of a firefighter physical demands analysis (PDA). The PDA involved cataloguing and weighing all firefighting equipment and describing the physical demands associated with firefighting tasks. This was selected by firefighters as a critical task and supported implementation of work restrictions and return to work plans and use of current evidence-based guidelines. Regular stakeholders meetings were conducted during the development of the PDA to ensure that the PDA could be used across multiple applications within the fire service. For example, the firefighters' return-to-work (RTW) specialist needed general information about firefighting tasks that could be modified to facilitate RTW. The occupational health and safety team, on the other hand, required detailed information to identify specific injury risks. The researchers and fire service were able to work together to review local information on job tasks/equipment/roles, PDAs from other municipalities, existing PDA development guidelines[7] and how information was used in various injury management decisions. The firefighters made key decisions about the format and content of the PDA, while researchers used best evidence guidelines[7] on PDAs to ensure quality. The fire service, insurers and employees now use this PDA to facilitate RTW, while occupational health and safety professionals use the PDA to identify tasks that predispose firefighters to injury. Building trust during our growing partnership was key to success in the making and implementation of the PDA as well to the development of FIRE-Well.

**The challenges of partnerships across "cultures"**

Although engaging all stakeholders through regular meetings ensured all perspectives were considered in developing FIRE-Well, the project was also met with challenges. The groups had different, sometimes conflicting, priorities and obligations. There were periods where research decisions were on hold for contract negotiations or leadership decision and periods where firefighters decisions were on hold waiting for funder decisions. One of the biggest challenges in this regard lay in the nature of the research process. Researchers know that research grants are not adjudicated immediately and are often unsuccessful on the first attempt. Stakeholders, experience frustration during the prolonged period of inactivity while waiting for grant funding and can lose the enthusiasm generated during the grant application process. Maintaining relationships and confidence in the partnership during these "hurry up and wait" cycles is a challenge.

We solved this challenge by maintaining engagement through ongoing meetings, reassuring our firefighter partners about the nature of the granting process and accomplishing small projects using internal resources and graduate students. For example, the work of graduate students enabled us to complete a qualitative study of the unique challenges faced by female firefighters. This study resulted in a publication[8], providing a much-needed success. Furthermore, as attention to gender differences grew in different fire services, our proactivity on this issue increased confidence around the usefulness of research.

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Once we were successful in receiving the Partnership in Health System Improvement (PHSI) grant for the FIRE-Well project, the firefighters and their stakeholders were immediately engaged in initiating the work. Firefighters are goal-oriented; this culture and focus, with regular communication, were critical to expediting FIRE-Well. One of the challenges in developing the screening component of the project was adapting protocols to be both valid and feasible. Researchers reviewed with firefighters the stages involved in the study and how the tasks were evolving to replicate the physiological and physical demands associated with firefighting. Once the research plan, space and protocols were established, the firefighters provided critical organization, allowing us to screen 150 firefighters in a six-month period. Their willing participation in this activity was seen as an indication of the level of commitment and partnership established between the researchers and fire service during the preliminary phases of this research program.

**Outcomes**

Our partnership with firefighters during the evolution and implementation of FIRE-Well has resulted in mutual benefits. As researchers, we have improved our understanding of the unique challenges of implementing KT in a complex occupational context; firefighters have gained insights into the nuances of developing and implementing a research program.

As a result of our partnership, a standardized evidence-based screening program has been developed and is being used by firefighters in injury risk identification. Our research findings are also supporting next phases, including the development of ergonomic modules that will be used to teach injury prevention strategies during high-risk firefighting tasks.

The outcomes from this research program will improve our ability to identify risk of injury among firefighters, improving their health and ultimately, that of the communities within which they serve.

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## Chapter Seven: Discussion

The series of studies that form this dissertation contribute to a program of research established in partnership with a local fire service. The overarching goal of the research partnership is to establish evidence-based injury management strategies that will alleviate challenges identified by the firefighters including: determination of factors that predispose firefighters to injury; developing strategies to reduce exposure to injury risk factors; and refining existing return-to-work processes. The results of this dissertation identified how individual attributes intersect with firefighter task performance and established a strong foundation to build future intervention research positioned to reduce injury frequency and improve firefighter work health. This discussion chapter summarizes the results of the individual studies, highlighting the primary findings of the thesis and how the dissertation contributes to three primary areas: (i) improved understanding of firefighter task performance, (ii) application of knowledge translation theory to occupational health research, and (iii) development of a measurement approach that can be used in applied, occupational contexts (see Appendix F). Limitations of the dissertation research and future directions are also discussed.

### Summary of dissertation results

A qualitative study conducted with female firefighters identified seven themes with common, underlying constructs related to the physical aspects of firefighting and developing approaches to mitigate injury risk. For example, *"Gender Related Differences"* reflected an identified need of female firefighters to focus on strength training to compensate for strength differences compared to their male counterparts. The theme *"Compensatory Strategies"* reflected how female firefighters associated asking for help with inability to perform the job, and subsequently developed individualized approaches to facilitate performing physically demanding aspects of firefighting. Overall, the study identified how gender shapes perceptions of job demands and job task performance suggesting that an improved understanding of firefighter task performance strategies while considering gender was necessary prior to developing injury prevention strategies. However, lacking in occupational health research is a reliable measurement approach, to identify task performance strategies in applied occupational contexts. Consequently, Dartfish movement analysis software was adopted to identify upper and lower body kinematics and postures associated with male and female firefighter task performance.

Dartfish relies on video-based inputs, which can be readily obtained from field-based research and from practitioners who might use this approach to facilitate occupational health and safety strategies (i.e., injury prevention, return-to-work planning). The unique contribution of this research is the context in which the data was collected and utilization of Dartfish analysis tools not previously used in the literature[1–5]. The hose drag task was performed in an applied context allowing firefighters to don full firefighting "bunker gear" and to utilize firefighting equipment. These conditions improve the generalizability of the study findings to the firefighting context, which is an important consideration when using this tool to evaluate impact of interventions designed to change task mechanics towards injury prevention or return-to-work in firefighting. Furthermore, strategies and recommendations were developed to facilitate data extraction using Dartfish and identified positional co-ordinate data was more reliable than angle data, particularly when quantifying body segments spanning multiple planes of movement.

Although ability to evaluate task mechanics is an important consideration in injury prevention, considering the impact of individual and physiological attributes on firefighter task performance will enable development of individualized training programs that will better prepare firefighters for the physically demands aspects of their job. Subsequently, the fourth study explored how individual and physiological attributes predicted firefighter task performance time during a hose drag task. The study identified that maximum strength generated during a static lifting task was identified as the overall primary, independent predictor of task performance time; when evaluating the predictive effects of the individual domains, individual's height, pre-task systolic blood pressure and maximum strength were significant predictors within each of the domains. The clinical implications of the study supports previous research[6–9] that strength is an important area of focus when developing individualized training programs focussed to improve firefighter task performance with a view on injury prevention.

The overall outcomes from this dissertation research contribute important insights into firefighter task performance postures and how gender is reflected in firefighting task performance. The anticipated impact of this evolving program of research is to improve firefighter work health. The research conducted in this dissertation was informed by the KTA framework[10,11], to ensure the research outcomes were contextualized to the fire service and firefighting context. The theoretical implications of this research suggest that knowledge translation theory enables the iterative, collaborative processes required for successful applied occupational health research[12,13].

## Contributions of Dissertation

The research studies in this dissertation contribute to research, theory and practice in three primary areas: (i) identifying firefighting task performance outcomes; (ii) application of theory in occupational health research; and (iii) measuring task performance indicators in occupational health research and practice (Appendix F).

### *Identifying Firefighter Task Performance Outcomes*

This dissertation has contributed to improved understanding of firefighter task performance through investigating the impact of gender and individual attributes associated with body postures, strength, cardiovascular fitness impacts on firefighting task performance. Although all study outcomes and results related to task performance, as a construct, task performance was viewed using multiple lens throughout the dissertation yet consistently related to the physicality of firefighting. For example, the qualitative study identified that female firefighters focus on strength training and modified task performance as strategies to overcome the physically demanding aspects firefighting. Female firefighters conceptualized task performance without consideration of quantifiable measures frequently used in occupational health and safety practice and research. For example, female firefighters reflected that strength training was an important consideration to ensure their ability to perform their job tasks at a pre-determined level (i.e., compared to their male counterparts). Furthermore, female firefighters adapted the way they performed tasks to accommodate for differences in muscle strength (i.e., more lower body strength vs. upper body strength).

These adaptations and strategies were implemented without direct measurements of muscle force outputs, object weight or in response to a calculated risk of injury. Female firefighters self-identified a functional differential between the job demands and their physical capability to perform the task demands; and subsequently developed strategies to mitigate those differences. Although the adaptation was in response to a self-identified limitation, research has also identified that female firefighters are more likely to have diminished physical abilities compared to male firefighters[14]. The same study further suggested that diminished health status including strength deficits could have implications for increasing risk of injury, injury to colleagues and impacts to the public[14]. Consequently, the female firefighters self-administered intervention to focus on training to improve physical capacity and task performance is an example of managing an evidence-based requirement-capability differential, although the strategy was based on subjective evaluation of task performance ability. These findings suggest a quantitative analysis of constructs typically associated with task performance may not always be required to facilitate change in task mechanics. Although how these adaptations impact work health and / or whether the same approach could be used to evaluate pre- and post-intervention status is unclear and are limitations of this approach. Developing quantitative methods to identify changes in task performance can be useful to evaluate the effectiveness of strategies positioned to mediate the gap between job requirements and individual capacity.

In contrast to the methods used to identify task performance in the qualitative study, quantitative approaches are commonly used in the literature to measure firefighter task performance including cardiovascular capacity[15,16], postural sway[17,18], general work postures[19] and performance time[7,20]. Often this research is conducted in controlled-laboratory settings providing valid, reliable outcomes however it is often challenging to adapt these approaches to field-based occupational health research. Consequently, the two subsequent studies in the dissertation (Chapters 3 and 4) sought to identify a reliable method that could be applied in occupational health research to assess kinematics associated with firefighting task performance. Few studies have analyzed firefighter kinematics although identifying kinematics associated with task performance provides useful insights into postures associated with risk of injury such as exposure to awkward, repetitive movements, sustained, forceful movements[21–23]. As well, identifying kinematics can be used to evaluate individual task performance differences particularly post-injury that might be useful in planning return-to-work. For example, individuals' task performance strategies may change following an injury; a kinematic approach can identify task performance adaptations and whether those adaptations may predispose the individual to further injury. This dissertation research (chapters 3 and 4) contributed a methodological approach that can be used to identify task performance kinematics in applied, occupational health research contexts.

This dissertation also considered task performance time as a measure of firefighter task performance. Performance time is frequently used in firefighter research[6–9] as firefighting and related emergency response tasks are often time urgent. This dissertation contributed additional research demonstrating the effects of individual factors such as demographics, strength and cardiovascular parameters on firefighter task performance. Although the variables selected for analysis didn't explain a significant portion of task performance time, the results provided insights into how individual factors impact task performance and in particular, the importance of strength in firefighting. Future research that considers integrating kinematics and time as measures of firefighting task performance may provide additional insights about the importance of modifiable variables (i.e., strength, cardiovascular fitness) as well as demographic characteristics (i.e., age, gender, height, weight) on task performance with implications for individualized training and injury prevention.

In summary, four of the studies in this dissertation contributed new knowledge about the construct of task performance, particularly the benefits of considering task performance from qualitative and quantitative approaches. Although this approach provided unique insights into firefighter task performance, variability of the construct may contribute to inconsistent findings particularly when considering evaluating task performance during intervention-based research. For example, identifying the effectiveness of interventions designed to mitigate workplace injury is challenging if inconsistent approaches are used to operationalize task performance. Furthermore, inconsistent effects of interventions in occupational health intervention research has been attributed to heterogeneity in methodology, improved documentation of the intervention and intensity of the intervention[24–26]. Theoretical models to facilitate identification of the "active ingredient" and to guide consistent methodology may improve outcomes in occupational health research. Although theoretical frameworks were not used to guide the specific studies, the overarching research was guided by the Knowledge-to-Action framework[10,11].

*Knowledge Translation Theory Development in Occupational Health Research*

Occupational health strategies reflect occupational health and safety policy positioned to protect and improve worker safety. Multiple, iterative consultations between employer-based stakeholders (i.e., manager, union, workers, ergonomist / allied health care professionals) are required to translate occupational health and safety policy into contextually relevant, effective injury management programs[27]. Although the Knowledge-to-Action (KTA) Framework was developed to inform translation of health evidence into practice[10,11], the components of the framework reflect a collaborative, transparent process, well suited to occupational health research and practice[13].

Briefly, the KTA Framework is a process model based on synthesis of multiple planned action theories[10,28]. The KTA Framework was developed to facilitate the process of implementing research evidence into practice to mitigate a knowledge gap. The framework is comprised of two primary processes: Knowledge Synthesis and an Action Cycle. Knowledge synthesis requires the synthesis of knowledge from multiple knowledge sources into a tool or product ready for implementation; the Action Cycle represents the iterative process of tool implementation[10,11]. The processes are intended to be responsive to the knowledge "end-users" to ensure that knowledge is relevant for the context in which it is being applied; stakeholders involved in the process are often the knowledge users as well as those who identified a knowledge gap. The CIHR Casebook chapter included in the dissertation (Chapter 6) reflects how the KTA framework informed the evolution of the research partnership with the fire service.

The important contribution of this casebook chapter falls within the wider context of occupational health research and how the KTA framework was adapted to inform occupational health research. One of the primary assumptions of the KTA framework is that the interaction between Knowledge Synthesis and the Action Cycle is fluid allowing exchange between components of the framework[11,28]. The inherent flexibility in the model allowed researchers to engage in collaborative discussions with the firefighters to ensure that research being conducted was relevant to their context. Furthermore, discussions ensured that research generated outputs were contextually relevant and could be readily implemented to improve firefighter work health. For example, the physical demands analysis (PDA) discussed in the casebook was one of the first projects completed in collaboration with the firefighters and provided an important tool (the PDA) that could be implemented by the firefighters in developing injury management strategies such as return-to-work planning.

Upon reflection of the model, the processes identified as most relevant within the KTA framework were in the Action Cycle; in particular “Contextualizing Knowledge to Context”, “Tailoring Interventions to Context” and “Assessing Barriers to Knowledge Use”. These components were also found to be the most relevant in previous research that involved developing and implementing a tool in an occupational context[13]. It may be the latter components of the Action Cycle (i.e., Monitoring Knowledge Use, Evaluating Outcomes and Sustaining Knowledge Use) will become more relevant as the research partnership progresses and with increased focus on intervention based research based on the foundational work identified in this dissertation. As the research partnership continues to develop and intervention-based research is conducted, there will be opportunity to reflect and identify how latter components of the cycle (i.e., Monitoring Knowledge Use, Evaluating Outcomes and Sustaining Knowledge Use) inform future collaborations and research projects.

A limitation of the KTA framework is that although it is able to guide knowledge synthesis and implementation processes in an occupational context, it is not directive with respect to enacting components of the model. For example, although "Contextualizing Knowledge to Local Context" is a critical phase in the KTA framework, there are no specific parameters provided to facilitate this process. Previous research noted the same limitation[13] and subsequently introduced additional guidelines to complete the tool development. One approach to expand the application of the KTA in occupational health research is to consider introducing directive models to standardize the measurement approaches concurrently with the KTA model particularly in the knowledge synthesis – tool development phase. As previously discussed, developing standardized approaches to operationalize task performance may improve ability to identify the effectiveness of interventions intended to impact task performance. Furthermore, using Process Evaluations[29] may provide further insights into the critical components of the KTA framework that are necessary for consideration when using to guide occupational health research.

In summary, this dissertation and associated research[13] contributed new knowledge regarding the application of the KTA framework to inform occupational health research involving a research partnership. Although the initial components of the Action Cycle have been the focus of reflection, it is anticipated that as the research partnership progresses and an increased focus on intervention based research occurs, latter components of the KTA model will become more relevant. Consideration of additional, directive models and approaches such as conducting Process Evaluations concurrently with the KTA Framework may improve understanding of the key components that result in successful implementation of occupational health research initiatives.

*Tool Development for use in Occupational Health Research and Practice*

When identifying a method for capturing body segment movements in occupational contexts, there are several factors that need to be considered including (i) the intended application (ii) the work context (iii) aptitudes of individuals using the method and (iv) resources available for data processing[30]. Multiple observational methods exist to assess risk factors associated with occupational tasks[30] however the tools are relatively administrative and aren't able to capture kinematics associated with occupational task performance[22]. Capturing kinematics provides insights into task performance biomechanics and provides a measurement approach that enables identification of changes associated with interventions designed to modify task performance postures[22,23]. Multiple portable methods[31–33] exist that may be used to assess movements and postures associated with occupational tasks however there is a paucity of literature relating their use to applied occupational health research. A primary consideration in developing these approaches for use in occupational health research and practice, is the primary end-user may be a clinician, worker or health and safety professional who may not have available resources to conduct complex computations or data processing skills[34,35]. Consequently, developing an approach that is accessible to clinicians, health and safety professionals, ergonomists, and employer stakeholders is necessary to ensure approaches can be translated to use in occupational health research and practice.

A unique contribution of the research conducted in Chapters 3 and 4 is development of a measurement approach in consideration of the various needs of the multiple stakeholders who were anticipated to use the resulting method. A systematic review identified that video and pictures was one of the most frequent tools used by ergonomists when conducting worksite assessments [30]. Dartfish software was selected for this study as it provides tools to analyze body segment postures and kinematics utilizing video based inputs. Furthermore, Dartfish has been established in the literature as a reliable method to identify kinematics associated with lower[2,36] and upper[3–5] body postures, and during lifting tasks[37]. These studies have established an important foundation to utilizing this movement analysis software in various research contexts through developing data collection methods and identifying measurement approaches associated with data extraction. However a primary limitation of the existing research related to applied occupational health research, is that methods were established in laboratory settings using controlled movements (i.e., Melton et. al.[3]). Before extending Dartfish to applied occupational health research, establishing measurement properties associated with extracting body segment postures and kinematics during complex movements in applied contexts, needs to be established[38]. A primary contribution of the dissertation research in Chapters 3 and 4, is identification of the relative and absolute reliability using standard error of measurement and the minimal detectable difference of using Dartfish when extracting upper and lower body postures during a field-controlled firefighting task. Reliability analyses identified that tracking angles was associated with more measurement error than tracking positional-coordinate data particularly when assessing body segments that rotated through the transverse plane. Relative reliability was higher when tracking single plane angles, during single frame analysis and tracking positional co-ordinates of complex body segment movements. Recommendations for extracting data using Dartfish were identified based on analysis of measurement properties associated with Dartfish and are reviewed below.

1. Identify camera position relative to the key positions from which data extraction is anticipated. Analyzing movements from a sagittal perspective results in fewer methodological challenges with respect to data extraction.
2. Utilize the “suspend tracking” feature in Dartfish when tracking positional coordinates or angle segments. This technique is necessary when movements / body segments transverse through multiple planes of movement and when objects or body segments move across the markers used to track body segment movements.

3. Reliability analysis indicates extracting positional coordinate data is associated with higher reliability properties (higher relative reliability; lower absolute reliability) particularly when tracking body segments through a translational plane.
4. Obtain relevant anthropometric measures to convert positional data to a clinically relevant outcome.
5. Reliability results suggest single frame analysis results in higher reliability properties compared to tracking angles particularly when analyzing body segments that move through the transverse plane (i.e., joints with multiple degrees of freedom vs. hinge joints).
6. Use tracking (positional or angle) when determining range of motion or movement variability associated with a task or variability.

In summary, Dartfish supports a suite of movement analysis tools that are accessible to users with varying levels of expertise[2], reducing the need for complex computational methods or data processing. Because movement in occupational contexts spans multiple planes, the study results suggest tracking positional data and single frame analysis are associated with fewer methodological issues and higher measurement properties. Using positional data to identify body segment postures can also provide insights into joint angle mechanics. For example, individuals' using 50% hip translation relative to body height are likely using more knee flexion to perform a task than those using 8% of hip translation relative to body height. Subsequently, the individuals with minimal hip translation (8%) are likely using more hip flexion and minimal knee flexion to perform the task suggesting that lifting body mechanics education may be warranted. Additional research is currently being conducted to identify coupling between body segment postures and between data extraction methods (i.e., single frame and positional coordinates) to enable extending the research to this application.

Clinical implications of those findings is that positional coordinate data is associated with fewer methodological challenges and subsequently would result in a more accessible method for health and safety personnel and clinicians who wish to adopt this approach in applied settings. Furthermore, tracking positional coordinates may be used to identify movement variability and critical changes in postures during task performance that may provide insights into individual adaptations used to perform various occupational tasks. For example, during a strenuous lifting task, identifying individual variability in hand and hip position during the task would provide insights into mechanisms that individuals adapt at the shoulder and knee without having to establish angle positions. Analysis is currently underway to identify movement variability associated with existing outcomes including angle and positional coordinate data.

A primary limitation associated with the established methods is that data was extracted in a "field-controlled setting". For example, video cameras were positioned on tripods in standard locations for all participants and the start and end positions of the task were clearly delineated. These parameters were implemented in accordance with best practice when obtaining video for kinematic analysis[39] however limit applicability to applied occupational research as it is difficult to control individual movements to a single frame of reference. Consequently, additional research is needed to determine whether the measurement properties identified in the dissertation research extend to more complex applied occupational contexts.

**Limitations**

Limitations of the individual studies are described in each of the manuscripts. Overall, the primary limitations of the dissertation as a whole are in two primary areas: the narrow context of the current research and the methodological approaches used to obtain kinematic and physiological based outcomes.

The research conducted to date has been with a single fire service, which has facilitated all aspects of the research process including obtaining funding, developing research priorities, implementing research methods, preparing manuscripts and submitting conference abstracts. This approach has resulted in successful evolution of research that has identified important aspects of firefighter health and established foundational components that will be important to developing evidence-based injury management strategies for the fire service. Although a benefit of collaborative-based research is that established outcomes are contextually relevant, the findings are also limited to that context; the way in which the research results extend to similar occupational contexts is unknown.

Recently funded research is intended to upscale current research findings to investigate work environment, exposure to critical events, gender and demographic attributes as predictors of work limitations and work injuries across fire jurisdictions through-out Ontario. Furthermore, the methodological approaches established in the dissertation will be used to identify impacts of individual attributes on firefighter task performance with a sub-sample of firefighters recruited throughout Ontario. The findings from this research will expand the context of the dissertation research while identifying the impact of geographical placement on firefighter work health.

Furthermore, the activities used to identify firefighter task performance were short duration tasks, in a controlled applied occupational context. Firefighting tasks are continuous and occur in environmentally demanding contexts. Consequently, the translational component of the task performance findings is limited. Future research including expanding application of Dartfish to less controlled contexts and using methods to assess physiological response during emergency response are being developed to improve the contextual validity of this research.

An additional limitation of the dissertation research is the methodology to determine kinematic and physiological outcomes was relatively restricted. Dartfish was the only tool utilized for assessment of kinematic outcomes where several additional applied movement analysis methods may have been considered[31,33]. Dartfish was utilized because of its established measurement properties[2,3,5,36] however, its utility compared to a similar measurement approach was questioned particularly with respect to methodological challenges when using the tracking feature[3]. Melton et al.[3] compared Datapac and Dartfish when analyzing shoulder movements and identified t27 instances where tracking parameter were modified using Datapac and 122 instances where tracking needed to be suspended to correct marker placement using Dartfish. Furthermore, Dartfish on average required 8 +/- 2.1 minutes per file to process a file using angle tracking compared to Datapac which required 3 +/- 1.5 minutes per file. Although

Datapac appeared to be more methodological efficient, the data processing required was more complex consequently, when identifying a tool for use in applied occupational health research and practice, Dartfish remains a viable option. Furthermore, Dartfish has recently released an “app” which enables instantaneous movement analysis feedback using mobile devices. Identifying measurement properties associated with the “app” compared to the full software is suggested before utilizing this approach in research contexts. Although Dartfish remains a feasible approach, it would be beneficial to consider Dartfish in comparison to other commercially available systems to ensure its continued viability in occupational health research and practice.

Furthermore, the physiological parameters measured in the dissertation represented basic cardiovascular outcomes (blood pressure and heart rate). Although these parameters provide valid measures of cardiovascular tolerance to activity and are used as general indicators of cardiovascular health, this approach did not allow continuous monitoring of cardiovascular response through task performance. Continuous measurement of cardiovascular response would provide further insights into variability in cardiovascular response to activity and enhance applications for use in live occupational contexts. Recently funded research will endeavour to use a more sophisticated analysis approach with the Zephyr BioHarness™ 3 and the Physiological Status Monitoring (PSM) Monitoring system to identify physiological measures associated with cardiovascular tolerance. The Zephyr BioHarness™ 3 and PMS monitoring system were developed with researchers to identify physiological response of individuals working in high stress occupational environments (i.e., space, emergency response, army) and provides continuous feedback on multiple measures including heart rate, breath rate and posture. Because this technology can be used during live fire suppression, the outputs from this approach will provide valuable insights into the cardiovascular load experienced by firefighters and will enable development of training programs and predictive outcomes that accurately reflect the occupational demands of firefighting.

**Recommendations for Future Research**

Recommendations for future research have been highlighted in the individual manuscripts. The following provides recommendations to extend the current program of research.

Expanding the research context to include other fire services would improve the overall contextual relevance of the research findings. Consideration of utilizing collaborative-based research to identify critical factors contributing to postures during task performance in similar occupational groups (i.e., paramedics, police) may expand our understanding of the relationship between task performance and work injury in occupations associated with intermittent periods of intense physical activity.

Using knowledge translation theory to inform the processes involved in collaborative-based research will provide insights into the critical phases that lead to contextually relevant, effective intervention-based research. Although knowledge translation is informed by multiple theoretical approaches[40,41], the KTA framework was highlighted in this dissertation. Utilizing other system-based knowledge translation theoretical frameworks (i.e., PARiS framework[42,43]) may provide additional insights into the determining factors of successful applied occupational health research.

Expanding methodological approaches using Dartfish including: comparison between positional coordinate outcomes and joint angles; analyzing outcomes associated with movement variability; and using a non-fixated camera position to capture movements associated with complete task performance would enable its use in more complex occupational health research contexts.

Finally, developing an algorithm based on critical occupational tasks, that uses individual attributes (i.e., strength, cardiovascular outcomes, demographic variables) to identify performance gaps compared to similar individuals within an occupational domain, would provide contextually relevant, individualized information about functional ability in comparison to job task requirements. This information would be useful in developing individualized training programs to mitigate identified gaps in functional ability and may be used to determine physical work readiness following a period of disability and treatment.

**Conclusion**

This dissertation offers initial research, conducted in partnership with a local fire service, to identify the relevant factors that predispose firefighters to higher risk of injury. A qualitative study established the importance of considering gender in firefighter work and identified important objectives for future research in the dissertation including task performance mechanics and adaptations to accommodate the physically demanding aspects of firefighting. Task performance as a construct was further considered in research analyzing kinematics and task performance time. The importance of theoretical frameworks to inform occupational health research with particular focus on knowledge translation was discussed as well as the significant contribution of recommendations to facilitate Dartfish analysis in applied research settings.

This dissertation research captures the importance of conducting collaborative-based research in applied occupational health context to ensure that outputs are relevant and utilized. Future research will expand on the important foundational elements established in the dissertation with the goal of improving firefighter health and subsequently, the health and safety of the communities within which they serve.

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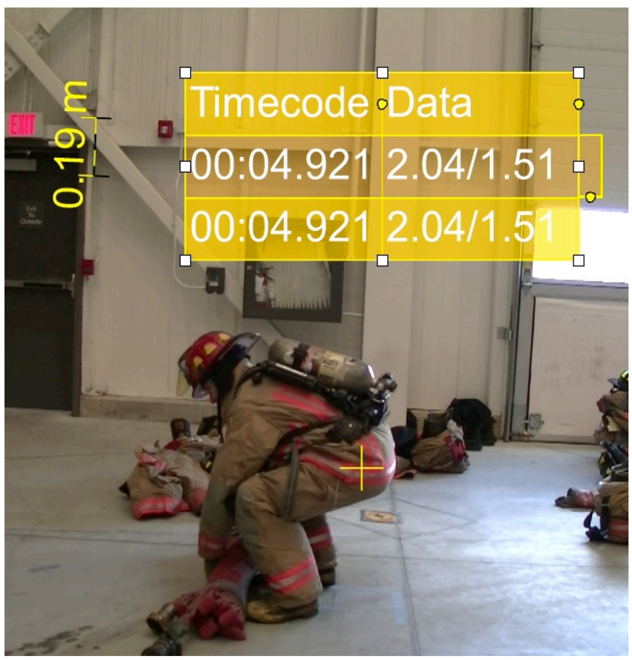
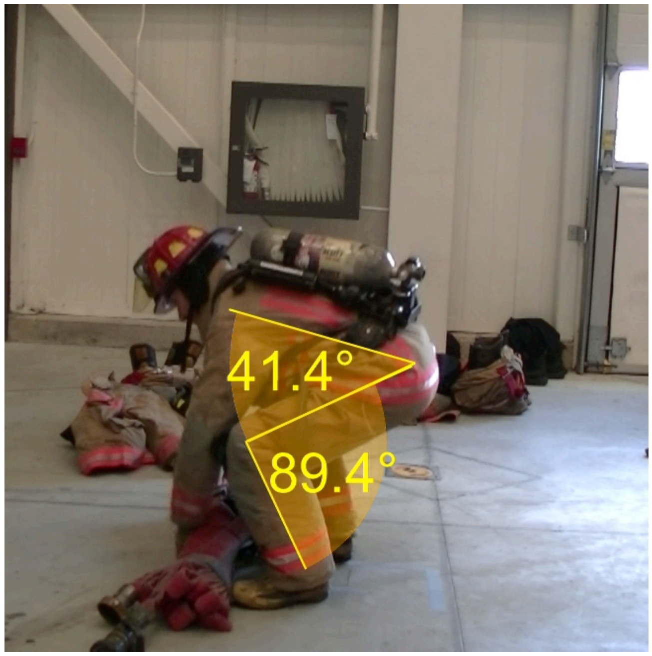
**Appendix A: Lower Extremity Dartfish Data Extraction Methods - Examples**


i.) Tracking Hip Angle: Frontal Camera Position




ii.) Tracking Hip x,y Positional Coordinates: Frontal Camera Position




iii.) Lower Extremity Single Frame Analysis (Knee and Hip): Frontal Camera Position


iv.) Lower Extremity (Knee and Hip) Single Frame Analysis: Sagittal Camera Position

## Appendix B: Participant Consent Form (Chapters 3 and 4)

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### PARTICIPANT INFORMATION SHEET

**Title of Study:** **The influence of individual and work factors on firefighter task performance**

**Local Principal Investigator:** **Dr. Joy MacDermid, PhD, McMaster University**
**Student Investigator:** **Kathryn Sinden M.Sc., C.K. McMaster University**

**Co-Investigators/ Supervisory Committee:** **Dr. Sandra Moll, McMaster University**
**Dr. Tom Jenkyn, Western University**

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You are being invited to participate in a research study about how firefighters perform different firefighting tasks. This is study is being conducted as part of a PhD thesis under the supervision of Dr. Joy MacDermid. If you choose to not participate, there will not be any negative consequences.

In order to decide whether or not you want to be a part of this research study, you should understand what is involved and the potential risks and benefits. This form gives detailed information about the research study which will be discussed with you. Once you understand the study, you will be asked to sign this form if you wish to participate. Please take your time to make your decision. Feel free to discuss it with your friends and family, and/or your family physician.

**Why is this study being done?**

Firefighting is a physically demanding job and firefighters experience high rates of injuries. This study is being conducted to help us understand how firefighters perform firefighting tasks and how individual factors (i.e., age, gender, height and weight) and work factors (i.e., difficulties performing work tasks) might influence the way that firefighting tasks are performed. Improving our understanding of how firefighting tasks are performed is anticipated to help future studies designed to reduce firefighters injuries.

**What is the purpose of this study?**

The purpose of this study is to determine:
1. The ability of a motion analysis system to capture and measure firefighting task performance.
2. To use motion analysis software to identify how firefighters perform fighting tasks.
3. To identify how different individual characteristics (i.e., gender, height, weight, age) and work factors (i.e., work task difficulty, organizational factors) influence how firefighters perform firefighting tasks.

**How many participants will be in this study?**

There will be a total of 50 study participants.

**What will be my responsibilities if I take part in the study?**

If you volunteer to participate in this study, there are several types of information that we would like to collect.

You will be asked to answer questions about organizational factors and any concerns or difficulties that you may have performing tasks at work. The surveys will take approximately 15-20 minutes to complete.

You will also be asked to perform two simulated firefighting tasks that will take approximately 45 minutes to complete. The tasks will be similar to the tasks you perform regularly as a firefighter. You will be asked to don your full bunker gear and markers will be placed on top of your firefighting equipment so that we can record your movements while you perform the two simulated firefighting tasks. You may also be asked to perform a single lift task that will require you to use your arms and legs. You will be videotaped while you perform these tasks so that we can analyze how you performed the lifting and firefighting tasks. At the end of all tasks, you will be asked about how difficult you found the tasks to perform and whether you experienced any pain or difficulty while performing the tasks.

**What are the possible risks and discomfort?**

You may feel worried about the screening identifying health problems and reporting of any difficulties that you have performing firefighting tasks. The results of your screening will be protected by confidentiality (your employer will not be informed) so you should not worry about this.

The firefighting tasks that you will perform are very similar to the firefighting tasks that you perform every day. The tasks will not be performed at the same intensity or for the same duration that you perform these tasks when you are at the scene of an emergency or fighting a fire. Therefore it is unlikely that you will experience any difficulties or get hurt when you are performing the firefighting tasks.

**What are the possible benefits for me and/or society?**

You may not directly benefit from this study. However, your participation will help researchers and clinicians better understand how firefighters perform firefighting tasks and ultimately, help to identify components of firefighting that put firefighters at risk for injury. This will help us develop programs specifically designed to reduce risk of injury and improve health, for firefighters.

**Will I be paid to participate in this study?**

You will receive a $15.00 Tim Horton's gift card as honorarium for your participant in the study.

**Will there be any costs to me in this study?**

There are no costs related to this study.

**What will happen to my personal information?**

Your name, age, date of birth, gender, home mailing address (including postal code), height, weight, job title, the number of years you've worked as a firefighter and contact information (home / cell phone number, personal email address) will be collected as part of this study. As well, if you participated in the previous FIRE-Well study, we may access your data and outcomes for comparison to similar outcomes in this study.

Your data will not be shared with anyone except with your consent or as required by law. Only the principal investigators of this study will have access to your data. All personal information will be removed from the data and will be replaced with a number. A list linking the number with your name will be kept in a secure place, separate from your file. The data, with identifying information removed, will be securely stored in a locked office in the research office. The data for this research study will be kept for 10 years following final publication of results.

For the purposes of ensuring the proper monitoring of the research study, it is possible that a member of the Hamilton Health Sciences/Faculty of Health Sciences Research Ethics Board may consult your research data. However, no records, which identify you by name or initials, will be allowed to leave the institution/university/hospital. By signing this consent form, you authorize such access.

If the results of the study are published, your name will not be used and no information that discloses your identity will be released or published without your specific consent to the disclosure.

**Can participation end early?**

If you volunteer to be in this study, you may withdraw at any time. Throughout the course of the study, you will be informed of any new information that might influence your decision to continue. If you wish to withdraw during or after the study, you have 2 options:

1) Continue to contribute the data collected prior to withdrawal.
2) Request that all your information and data be withdrawn completely from the study.

You may also refuse to answer any questions you don't want to answer and still remain in the study. The investigator may withdraw you from this research if circumstances arise which warrant doing so.

**What happens if I have a research-related injury?**

There is little threat of a study-related injury. If you are injured as a direct result of taking part in this study, no compensation will be provided to you by Hamilton Integrated Research Ethics (HIREB) or the Researchers.

However, you still have all your legal rights. If you sign this consent form it does not mean that you are releasing the investigator(s), institution(s) and/or sponsor from their legal and professional responsibilities.

**If I have any questions or problems, whom can I call?**

If you have any questions about the research now or later, please contact the PI: Kathryn Sinden at 905-525-9140 x26410 or sindenk@mcmaster.ca.

This study has been reviewed by the Hamilton Integrated Research Ethics (HIREB). The HIREB is responsible for ensuring that participants are informed of the risks associated with the research, and that participants are free to decide if participation is right for them. If you have any questions about your rights as a research participant, please call The Office of the Chair, HIREB at 905-521-2100 ext.4201

**CONSENT STATEMENT**

**SIGNATURE OF RESEARCH PARTICIPANT**

**I have read the preceding information thoroughly. I have had the opportunity to ask questions, and all of my questions have been answered to my satisfaction. I agree to participate in this study. I understand that I will receive a signed copy of this form.**

_______________________________________________

Name Signature Date

**OPTIONAL**

Do you wish to be contacted to participate in future research studies? YES ☐ NO ☐

**If YES, please fill out the fields below:**

Home Phone #: ______________________________

Alternate contact phone # (please circle: work / cell ): ______________________________

Personal Email Address: ______________________________________________________________

Person obtaining consent:
I have discussed this study in detail with the participant. I believe the participant understands what is involved in this study.

_______________________________________________

Name, Role in Study Signature Date

**Appendix C: Data Collection Protocol (Chapters 3 and 4)**

Protocol for "The influence of individual and work factors on firefighting task performance"

**OBJECTIVES**

The Problem

Firefighting is a physically demanding occupation. Understanding the mechanics involved in performing firefighting tasks will provide valuable insights into the factors that affect firefighting task performance and provide critical information to inform future intervention studies designed to mitigate injury risk.

The Research Question

The primary research objectives of this study are to determine:

1. The reliability and validity of motion analysis software that can be used in occupational and clinical settings to identify mechanics of complex movements.

2. The mechanics used by firefighters to perform firefighting tasks.

3. How personal factors (i.e., gender, height, weight, age, years of experience) and work factors (i.e., organizational policies and practices) influence firefighting task performance.

**METHODS**

Design

Observational cohort

Participants

Sample size = 50

Inclusion criteria:
- Active duty firefighters in the Hamilton District
- Fluent in English

Study Protocol

We devised a protocol that will identify how different individual and work factors affect firefighters performance of a simple lift task and two firefighting tasks. All firefighters (n=45) will complete the following baseline questionnaires to identify any limitations that they experience at work.

a) Work-Limitations Questionnaire-25 (WLQ-25) [1]
b) Patient Specific Functional Scale (PSFS) [2]
c) Organizational Policies and Practices (OPP) [3,4]

Firefighting tasks identified as high risk tasks in collaboration with firefighters, results of the physical demands analysis and in consideration of literature identifying high risk tasks, will be analysed using Dartfish software. Three tasks will be identified. Participants will be asked to perform firefighting tasks identified as high risk while wearing full turnout gear (weighing approximately 23 kg.), gloves and helmet. A marker will be attached to firefighter gear to facilitate identification of movement trajectories. Two high-resolution video cameras will be positioned in sagittal and coronal planes to capture upper and lower body movement trajectories in firefighting tasks previously identified. The two high-resolution video cameras will be connected directly to a computer laptop. Each participant will perform the three identified tasks one time only.

All firefighters (n=45) will then perform a simple lift task that will involve them bending at the knees and lifting a crate with weights (total weight = 30 lbs (max). They will then be asked to perform of two simulated firefighting tasks (e.g., stair climb, hose drag) identified as high risk tasks in collaboration with firefighters, results of the physical demands analysis and in consideration of literature identifying high risk tasks. The firefighters will be videotaped while performing these tasks for movement analysis and to identify the accuracy of the motion analysis system. Participants will be asked to perform the three tasks (lift task and two firefighting tasks) while wearing full turnout gear (weighing approximately 23 kg.), gloves and helmet. A marker will be attached to firefighter gear to facilitate identification of movement trajectories. Two high-resolution video cameras will be positioned in sagittal and coronal planes to capture upper and lower body movement trajectories in firefighting tasks previously identified. Each participant will perform the three tasks (lift task, two firefighting tasks)one time only.
Blood pressure and heart rate will be taken pre- and post task performance. An assessment form will be developed to standardize the way the tasks are performed. An individual trained in assessing movement will facilitate the task performance protocol and will examine:

- Individual movement mechanics used while performing firefighting tasks

- Self-rated task difficulty using the 10-point Borg scale. An example of a question using the 10-point Borg scale is:

"On a scale of 1-10 where 1 is Like nothing at all and 10 is Very, very hard, please tell me how difficult you found the hose drag task."

- The participants will also be asked about pain and measure the type and location of pain experienced by the participants while performing the simulated firefighting tasks. For example:

  "While performing the hose drag task did you experience any discomfort or pain? If so, where and please describe the type of discomfort that you experienced. Is it radiating or localized to one specific area? Do you still have the discomfort / pain or has it gone away? Please rate your pain on a scale of 1- 10 where 1 is no pain and 10 is the worst pain that you have ever experienced.

Once the firefighters have performed the lift task and the firefighting tasks, the video images will be imported into motion analysis software. The motion analysis software will be used to identify different movement parameters (i.e., the angles of movement, speed of task performance). These outcomes will be compared to measurement standards to determine the validity of the motion analysis system. The outcomes will also be compared between two different assessors who are familiar with the motion analysis system to confirm the reliability of the motion analysis software to measure movement parameters during simple tasks (i.e., the lifting task) and complex movements (i.e., the firefighter tasks). The motion analysis system will then be used to identify how firefighters perform different tasks by analyzing movement parameter outcomes (i.e., angles of movement, speed of movements). The influence of individual differences (i.e., sex, height, weight, tenure) and difficulties reported with performing firefighting tasks during task will then be entered into a regression model to identify how personal factors and work factors might influence firefighting task performance.

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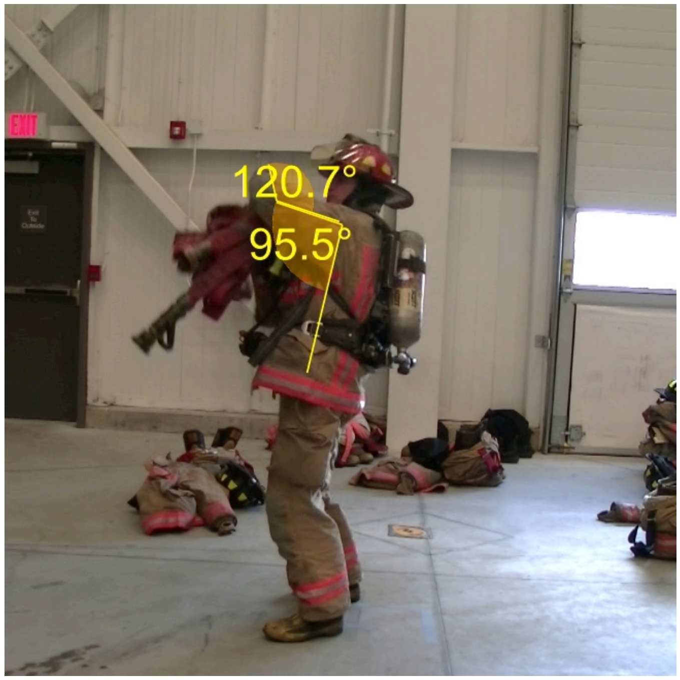
**Appendix D: Upper Extremity Dartfish Data Extraction Methods – Examples**


i.) Tracking Elbow Angle: Frontal Camera Position

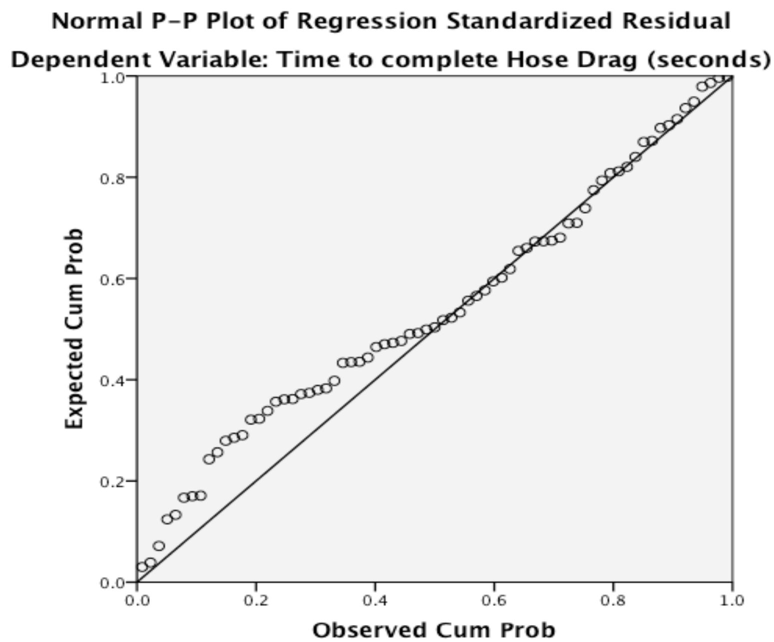

ii) Tracking Hand x,y Positional Coordinates: Frontal Camera Position

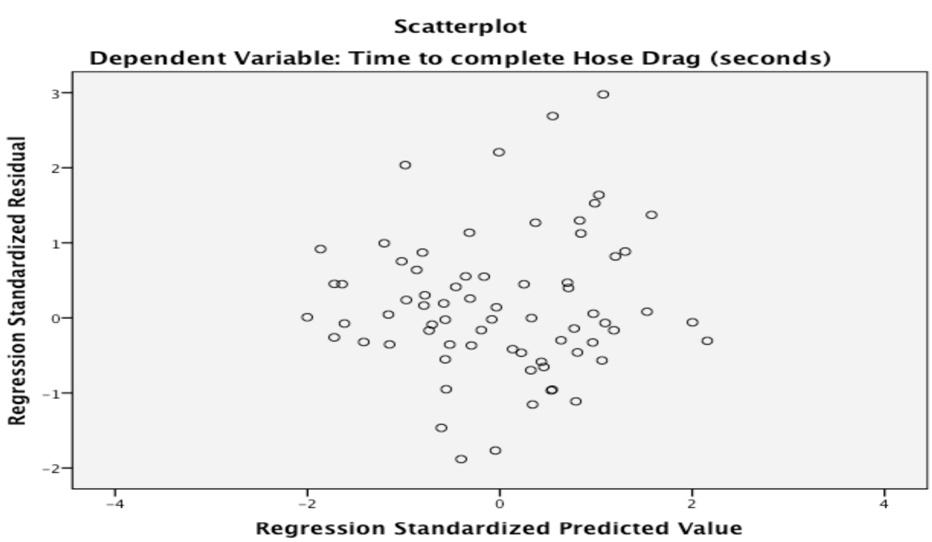



iii.) Upper Extremity (Elbow and Shoulder)
Single frame analysis: Frontal Camera Position


iv.) Upper Extremity (Elbow) Single Frame Analysis:
Frontal Camera Position

**Appendix E. Regression Analysis: Diagnostic Results**



**Appendix F: Thesis Contributions Informed by Knowledge Translation**