Towards the establishment of a worker-centered framework to physically prepare firefighters

The evaluation of movement and the transfer of training

by

David Frost

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Doctor of Philosophy
in
Kinesiology

Waterloo, Ontario, Canada, 2013

DECLARATION

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

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

David Michael Frost

ABSTRACT

Firefighter injuries are a billion dollar problem every year with an even larger human impact. Substantial efforts have been made to reduce the associated costs, yet many of the injuries sustained are the director result of efforts to become better physically prepared. Because firefighters depend on their physical abilities to perform safely and effectively, worker-centered strategies, wherein an emphasis is placed on *how* individuals perform are needed. However, to date, there is little evidence to help guide the evaluation of an individual's movement patterns, particularly within the context of their occupation, and even less known about the transfer of training. To assist in the establishment of a worker-centered framework that can be used to physically prepare firefighters, four studies were conducted to address the following global thesis objectives:

1) Examine the impact of task and environmental constraints on individuals' movement behaviour.
2) Examine the impact of exercise on individuals' movement behaviour.
3) Examine the homogeneity of individuals' movement behaviour.

Study 1: Movement variability and the estimation of "meaningful" change

Background: The within-subject variation may offer a viable means to examine the individual so that studies are not limited to group analyses. Study objectives were to examine the within-subject variation and between-session repeatability of select descriptors of motion and evaluate the potential in using the within-subject variation as a criterion with which to define biologically significant or "meaningful" within-subject differences.

Methods: Twenty professional firefighters were assigned to a lifting or firefighter group, each completing three testing sessions. Participants performed 25 repetitions of two lifting (heavy and light) or two simulated firefighting tasks (hose advance, forced entry). The magnitude and within-subject variation of select kinematic measures were described for each session, and sequential averaging was used to explore the efficacy of using the within-subject variability to define “meaningful” within-subject differences.

Results: All dependent measures were repeatable for each of the four tasks examined; however, the individuals did not exhibit the same movement patterns as were demonstrated by the group. Using only 2 (of 25) repetitions, the within-subject variation successfully captured the 25-trial variation in 70% of all instances; using 3, 5, and 10 trials increased the success rate to 74%, 81% and 89%, respectively.

Conclusions: Aggregate data may not represent that of the individuals, and therefore it might be important to examine within-subject changes to correctly interpret the effects of an intervention. The within-subject variation may offer a simple means to accommodate participants’ variability without having to collect a large number of trials, and thus could provide a tremendous opportunity to explore various interventions designed to prevent musculoskeletal injury or improve performance.

Study 2: Load, speed and the evaluation of movement: A task’s demands influence the way we move

Background: If individuals adapt their movement patterns in response to the demands of a task, the utility of movement evaluations comprising only low demand activities could be limited. The study objective was to determine whether individuals adjust their movement patterns in response to variation of the external load and speed of movement.

Methods: Fifty-two professional firefighters performed five low-demand (i.e. light load, low movement speed) whole-body tasks (i.e. lift, squat, lunge, push, pull). Once each task had been performed its demands were modified by increasing the movement speed, external load, or speed and load. Select measures of motion were used to characterize the performance of each task and comparisons were made between conditions.

Results: Participants adapted their movement patterns in response to the demands of a task (64% and 70% of all variables were influenced ($p<0.05$) by changing the load and speed, respectively), but in a manner unique to the task and type of demand in question, and not always in the same way as that of the group. During the first phase of each task, there were 246 individual "meaningful" negative adaptations observed in response to an increase in speed, but only 125 in response to the heavier loads.

Conclusions: Simply because an individual exhibits the ability to perform a low-demand task does not imply that they will also be physically prepared to perform safely or effectively when the task's demands are increased. Movement screens comprising only low demand activities may not adequately reflect an individual's capacity, or their risk of injury, and could skew any recommendations that are made for training.

Study 3: The predictive value of general movement tasks in assessing occupational task performance

Background: Attempts to generalize the results of a movement evaluation or screen may lead to inaccurate characterizations (e.g. high risk) and inappropriate recommendations for training. The study objective was to investigate whether a battery of general tasks could be used to describe the movement patterns adopted to perform select job-specific skills.

Methods: Fifty-two professional firefighters performed a battery of general (i.e. lift, squat, lunge, push and pull) and occupation-specific (i.e. chop, forced entry, hose drag, hose pull, heavy drag) tasks that simulated the demands of firefighting. Participants' peak spine flexion, range of spine lateral bend and twist, and peak medial displacement of each knee in the frontal plane were compared across tasks.

Results: The general tasks could be used to estimate the magnitude of spine and frontal plane knee motion adopted while performing the battery of complex firefighting-specific skills. In only 14.6% of all instances across variables and tasks were individuals' general task scores not greater than those observed during the firefighter skills. There may be attributes, or "key features", of an individual's movement behaviour that can be used to generalize their movement competency across a range of activities.

Conclusions: The findings provide support for the notion that a general whole-body movement evaluation, or pre-participation screen, can be used to estimate an individual's risk of injury or make recommendations for training, provided that the screening tasks are chosen and administered in such a way that they challenge participants' capacity to control the motions of interest.

Study 4: Periodized exercise and the transfer of training: Can we change the way an individual moves?

Background: Exercise programs that emphasize fitness characteristics and performance outcomes alone may not offer an effective means to elevate one's level of physical preparedness. The study objective was to examine the adaptations (fitness and movement) exhibited by professional firefighters in response to two training methodologies, differing most notably in the attention that was given to *how* each exercise was performed. Five tasks not included in the interventions were used to evaluate the transfer of training.

Methods: Fifty-two firefighters were assigned to a "movement-oriented fitness" training (MOV), "fitness" training or control (CON) group. Before and after 12 weeks of exercise, subjects performed a comprehensive fitness evaluation and laboratory test, comprising five general whole-body tasks. Participants' peak spine flexion, range of lateral bend and twist, and peak medial displacement of each knee in the frontal plane were quantified.

Results: FIT and MOV exhibited significant improvements in nearly all aspects of fitness tested; however, only MOV demonstrated less joint motion while performing each transfer task. FIT showed select improvements, although spine flexion and frontal plane knee motion increased while squatting, lunging, pushing and pulling. More and fewer MOV participants exhibited *only* positive and negative "meaningful" post-training changes, respectively, in comparison to the FIT and CON groups.

Conclusions: A well-designed exercise program can be used to change an individual's habitual movement patterns, which for occupational athletes such as firefighters, soldiers and police officers, implies that training can have a direct impact on their safety and effectiveness. However, emphasizing fitness characteristics and performance outcomes alone may not be the most effective strategy to reduce one's risk of injury or elevate their level of preparedness.

Summary and Conclusions:

An individual’s movement patterns are variable and influenced by the task and environmental constraints (e.g. speed of movement). Therefore, whether attempting to prevent injury, enhance performance or improve one’s quality of life, any physical preparation program should give adequate consideration to the individuals’ adaptations. When focused solely on the group’s behaviour, there is greater opportunity to skew the interpretation of any findings and overlook several important and potentially novel insights regarding the movement-related adaptations that are exhibited by each individual in response to the particular stimulus, demand, or exercise being investigated.

Although several novel insights were provided by the findings of this thesis, the most practical and perhaps influential was that a well-designed exercise program can change an individual’s habitual movement patterns. A group of firefighters with little knowledge or appreciation for how they move, exhibited more control and coordination while performing five whole-body transfer tasks following twelve weeks of training. There is no single exercise or coaching cue that can be used to improve every individual’s capacity; however, one inappropriate recommendation can negate any potential benefit that a program can offer. Consequently, critical to the establishment of a worker-centered framework to physically prepare firefighters is an appreciation for movement and the transfer of training.

ACKNOWLEDGEMENTS

I will be forever indebted to my friend and mentor, Stu McGill for giving me the opportunity to pursue such a fascinating area of work. He showed a great deal of trust in my abilities while continually challenging my thought process so that I could grow both personally and as a scientist. His passion and dedication are inspiring and something that I will try to emulate for the rest of my career.

I also owe a great deal of gratitude to my friend and mentor, Jack Callaghan. He provided an outstanding learning environment and was unwavering with his encouragement and support. Words cannot express how fortunate I feel to have had an opportunity to work with such well-respected, highly productive individuals, who lead by example in their professional and personal lives every single day.

Thesis committee members, Richard Wells and Philip Bigelow posed thought provoking questions and challenged me to reflect on what I truly wanted to accomplish with this work. I strongly believe that their feedback has assisted to make this thesis much more impactful. Similarly, external examiner, Deydre Teyhen, provided a unique perspective and offered insights that will be critical to my growth as a scientist for years to come.

The University of Waterloo provides a wonderful environment for students to excel and pursue their interests, and as such, a number of faculty members and administrative, technical and support staff were paramount to the completion of my degree. At the risk of leaving someone out I would like to express a heartfelt thank you to Clark Dickerson, Andrew Laing, Steve Prentice, Ruth Gooding, Denise Hay, Wendell Prime, Jeff Rice, Craig McDonald, Lowell Williamson, Caryl Russell, Lori Kraemer, and Erin Harvey.

There were also several organizations and individuals who believed in this work and contributed significant expertise and resources to ensure its success. I would like express my sincere appreciation to Kevin Elsey, Craig Friedman and Mark Verstegen from Athletes' Performance for believing in a big idea and allowing me to collaborate with such a wonderful team. Jeff Sassone, Dan Burns, Anthony Slater, Alex Lincoln, Russ Orr, Anthony Hobgood, Andrew Fisher, Harold Hill, Bob Calvin, Paul Caldwell, Brett Bech, Andy Barnett, Steve Smith, Amanda Carslon-Phillips, Sue Falsone, Nick Winkleman, John Stemmerman, Joe Gomes, and the AP interns, it is only because each of them made a commitment to this work that we were able to achieve such success.

The Andrews Institute opened their doors to two students from Canada and immediately gave them a home away from home. The kindness and generosity of Chad Gilliland, Erik Nilssen, Lynn Hare, Sherry Gammache, Tommy Johnson, Judy Pickington, James Andrews, Lonnie Paulos, Rafael Escamilla and Michele Ionno will not be forgotten.

I would like to acknowledge Baptist Health Care, the City of Pensacola, the City of Waterloo and every firefighter from the Pensacola, Kitchener and Waterloo Fire Departments who sacrificed countless hours of their own time. In particular, I will forever be in debt to Frank Edwards, Russell Beaty, Paul Madison, David Allen, Brock Jester, Luke Pedersen, Larry Brassard, Joanne Marchildon and John Pedersen for their support and enthusiasm for this research from the very beginning. Further, I would like to extend a sincere thank you to Ian Crosby and George Cruz for inspiring me with their passion for the fire service. I am humbled every day by the noble acts of firefighters.

I would also like to express my gratitude to Northern Digital, C-Motion, Vicon (Derek Potter), the Centre of Research Expertise for the Prevention of Musculoskeletal Disorders and the Natural Sciences and Engineering Research Council of Canada. This work would not have been possible without their support.

I strongly believe that nothing of this magnitude could ever be accomplished without the support of extraordinary friends. Tyson Beach, Matt Kritz, Chad Gooyers, Luke Pedersen, Jordan Andersen, Chad Fenwick, Sam Howarth, Steph Freeman, Tom Karakolis, Diana DeCarvalho, Steve Fischer, Ed Cambridge, Natalie Sidorkewicz, Christian Balkovec, Christina Popovich, Sandy Wright, Janice Moreside, Rob Parkinson, Kaitlin Gallagher, Jennie Jackson, Troy Campbell, Ben Pickard and Rob McMillan has each contributed to making my last five years a wonderful experience.

It is important to further acknowledge the positive influence that Tyson Beach and Matt Kritz have had on me as both a scientist and a man. Each is an exceptional friend who has transformed the way that I think about science, business, leadership, coaching and life. I look forward to working with them, sharing ideas and changing the world☺.

My mother, father and two brothers (Brock and Chris) have always encouraged me to follow my dreams. Their unconditional love and support has contributed to making this a wonderful journey and is part of the reason why I am the man I am today.

I must also give a heartfelt thank you to Jos and Sharon van Diepen for raising such a compassionate daughter and making me feel like part of the family for the past twelve years. It truly has been a blessing to have such a kind-hearted family in my corner.

Lastly, this has been a wonderful experience made all the more worthwhile by having an amazing person to share it with. Sixteen years, three countries, three universities, five degrees and not once did I lose support from my best friend of the love of my life, Kelly. Words cannot express how special it is to have a partner that inspires me to be a better person every single day with her kindness, generosity and words of encouragement. I intend to spend the next sixteen years making sure that she knows how much it has meant.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

INTRODUCTION

1.1. BACKGROUND

Firefighting is an unpredictable and high-risk occupation. Incumbents are commonly exposed to perilous environments wherein the physical requirements of the job-tasks may exceed their ability to perform in a safe and effective manner. Poor preparation (e.g. inadequate job-training, inappropriate physical training) may increase a firefighter's risk of injury and increase the potential for danger to co-workers and the very people they aim to protect. Tremendous efforts have been made by organizations such as the International Association of Fire Fighters (IAFF) to highlight the potential human and economic impact of injuries on society and approximately $1 billion is now spent annually in the United States on prevention alone (TriData, 2004). As a direct outcome of these efforts, the total number of injuries sustained by firefighters has been reduced, though unfortunately, the results can be attributed entirely to fewer fires; the rate of fireground injuries has not changed for thirty years (Karter Jr and Molis, 2010). In fact, the incidence of strains and sprains (musculoskeletal injuries), which account for approximately half of all fire-related incidents, has doubled since 1981. Firefighting is and always will be a physically demanding occupation and thus all injuries will never be avoided, but the effectiveness of prevention programs may improve if a framework is established so that the notion of being physically prepared can be viewed in a context related to one's job, or life.

Every individual lives with a unique set of physical demands (e.g. frequency, intensity, duration) that stem from tasks they need to do (job-related) or want to do (life-related). For firefighters, these demands may reflect the skills necessary to safely fight a live fire or effectively assist at the scene of an accident, but they also encompass those activities that each of them performs when they go home at the end of the day – going for a run, doing chores around the house or playing with their kids. To perform safely and effectively, each firefighter must exhibit sufficient capacity (i.e. the ability, awareness and understanding) to match their specific demands, because in the unfortunate event that demands do exceed capacity, their risk of sustaining a musculoskeletal injury will increase. Quantifying an individual's demands and capacity at the tissue level (i.e. applied load and tissue tolerance), is critical to truly appreciate their risk of injury; however, this level of detail was beyond the scope of this thesis. Instead, demands and capacity were described in a global sense with the aim of providing a preliminary step towards the establishment of a worker-centered framework that could be used to physically prepare occupational groups such as firefighters. This approach may be overly simplistic; however, it does offer a foundation from which to design future training or injury prevention programs for the individual; efforts can be targeted to reduce demands (i.e. task-centered) and/or enhance capacity (i.e. worker-centered).

Task-centered strategies aim to *fit tasks to workers* and are based on fundamental principles of ergonomics science. The "margin of safety" is increased by attenuating task demands without specifically addressing worker capacity – an excellent approach for certain aspects of the job (e.g. truck design). However, a firefighter's performance is heavily influenced by their physical abilities and tasks may be repeated at irregular intervals under different environmental conditions and situational constraints. Consequently, worker-centered strategies that place an emphasis on improving capacity may be better suited to reduce the incidence of injury within the fire service, or at a minimum, the incidence of injuries sustained while performing non-modifiable tasks. Efforts are made to *fit workers to tasks*, or, best prepare firefighters to meet their specific demands. However, being physically "fit" in the traditional sense, defined herein as having a certain level of muscular strength, endurance, cardiorespiratory efficiency, etc., may also leave firefighters ill-prepared for the demands of their job. In 1997, motivated by the prevalence of firefighter injury, the IAFF established fitness standards for new recruits and physical preparation guidelines for incumbents (International Association of Fire Fighters). Although an excellent initiative, the incidence of injury has not changed and unfortunately many of those incurred have been the direct result of efforts to increase one's level of fitness (e.g. strength, endurance, power and cardiorespiratory efficiency) (Almeida et al., 1999, Jones et al., 1993b, Knapik et al., 2001). In fact, Poplin et al. (2012) recently reported that one third of all injuries sustained by the Tucson Fire Department, a medium-sized department comprising approximately 650 members, between 2004 and 2009 resulted from physical exercise activities. Fitness is essential, particularly for firefighters, but emphasizing any physical ability alone without considering the individual's awareness or understanding of the task will not ensure peak performance and long-term durability (Herman et al., 2008, McGinn, 2004). Fitness simply reflects an individual's potential capacity. In other words, having excellent strength or endurance, for example, does not *limit* one's ability to perform safely and effectively; nor does it imply that they will. Firefighters need to be sufficiently *fit to move* in such a way that their capacity matches/exceeds the demands of the task. Though often overlooked, one of the most critical factors in predicting who will and who will not become injured might be the way that individuals move.

An individual's movement patterns may be modified (either voluntarily or involuntarily) in response to perceived demands or through knowledge gained from previous experiences. Depending on the particular strategy chosen, challenging tasks can be made to be very simple and seemingly mundane chores can become injury-causing events. Because the way an individual moves reflects their capacity to perform within the context of a task's external demands (i.e. do they exhibit undesirable motion?), efforts to examine the injury risk and physical preparedness of an individual may be improved by including a movement evaluation. But movement patterns are inherently variable (both between and within individuals) (Dufek et al., 1995, James and Bates, 1997, James et al., 2007) and likely task- and demand-specific. As a result, it may be important to consider the demands of a task (e.g. load, speed, duration) when evaluating the parameters selected to describe motion; simply because an individual exhibits a particular pattern, perceived to be "good" or "bad", does not mean that they had to (they may have had ability) or that they would perform in a similar manner if asked to perform other tasks of varying demands. Additional research is needed to investigate the degree to which an individual's motion characteristics are modified across conditions (tasks and demands) and influenced by various factors (e.g. coaching and exercise), so that as a scientific community we can better interpret their utility in predicting injury or guiding the design of an intervention. Such knowledge will also assist us to better evaluate the effectiveness of various training programs and facilitate the development of long-term sustainable training strategies for any physically demanding occupation. However, fundamental to understanding the role of movement and its application to the overall physical preparation of firefighters is an appreciation for the fact movement patterns are inherently variable; no two individuals will exhibit identical movement strategies or adapt in the same way to training.

This thesis sought to investigate several questions pertaining to the evaluation of movement and the transfer of training, although the global objective was to assist in the establishment of a worker-centered framework to physically prepare occupational groups such as firefighters. It was anticipated that the knowledge gained would assist in the development of better guidelines to evaluate a firefighter's capacity and direct any recommendations for training. Worker-centered physical preparation is defined herein as placing an emphasis on the individual – *their* capacity is evaluated, *their* information is interpreted (fitness and movement) and recommendations are made to enhance *their* performance and long-term durability. Fundamental to this approach is an appreciation for the fact that there are several factors (e.g. between-trial variation, a task's demands) that may influence our interpretation of an individual's movement patterns. Furthermore, the success of any intervention (exercise of otherwise) is arguably dependent on its ability to alter the motion strategies employed to perform tasks beyond those used for training; there must be an observable transfer. Improving an individual's gym-based performance alone may not elicit the most favorable adaptions with regards to preventing injuries, improving performance or enhancing their quality of life.

1.2. SIGNIFICANCE

This thesis will assist in the establishment of a worker-centered paradigm to physically prepare occupational groups such as firefighters, soldiers and police officers by answering fundamental questions pertaining to the description and evaluation of movement patterns and the transfer of exercise. It is anticipated that this work will offer scientists and practitioners novel insights into movement screening, exercise prescription and the physical preparation of occupational groups, and provide a framework for future research.

1.3. GLOBAL THESIS OBJECTIVES

Firefighter injuries are a billion dollar problem with an even larger human impact. Substantial efforts have been made to reduce the associated costs, yet many of the injuries sustained are the director result of efforts to become better physically prepared. Because firefighters depend on their physical abilities to perform safely and effectively, worker-centered strategies, wherein an emphasis is placed on *how* individuals perform are needed. However, to date, there is little evidence to help guide the evaluation of an individual's movement patterns, particularly within the context of their occupation, and even less known about the transfer of training. To assist in the establishment of a worker-centered framework that can be used to physically prepare firefighters, four studies were conducted to address three global thesis objectives:

1) Examine the impact of task and environmental constraints on individuals' movement behaviour.
2) Examine the impact of exercise on individuals' movement behaviour.
3) Examine the homogeneity of individuals' movement behaviour.

1.4. THESIS OVERVIEW

This thesis comprised four studies (Figure 1.1), each largely focused on the movement patterns used to perform tasks of varying complexity and demand. Study one provided the foundation for this thesis by investigating the between day-variation in select movement-related variables that were used to characterize the tasks examined throughout this thesis. The study was also used to evaluate the potential in using participants' variation as a criterion with which to define biologically significant or "meaningful" within-subject differences between testing conditions or following an intervention. Study two examined the way that individuals adapt their movement patterns in response to changing a task's demands (i.e. load and speed of movement). Study three explored the notion of task specificity and the generalizability of an individual's movement behavior by contrasting the movement patterns used to perform general tasks with those specific to firefighting. The final study of this thesis explored the fitness- and movement-related adaptations exhibited by professional firefighters in response to two exercise programs, differing most notably in the attention that was given to *how* each exercise was performed. Participants movement-related adaptations were evaluated post-training with five "transfer" tasks, for which they received no formal coaching or feedback.

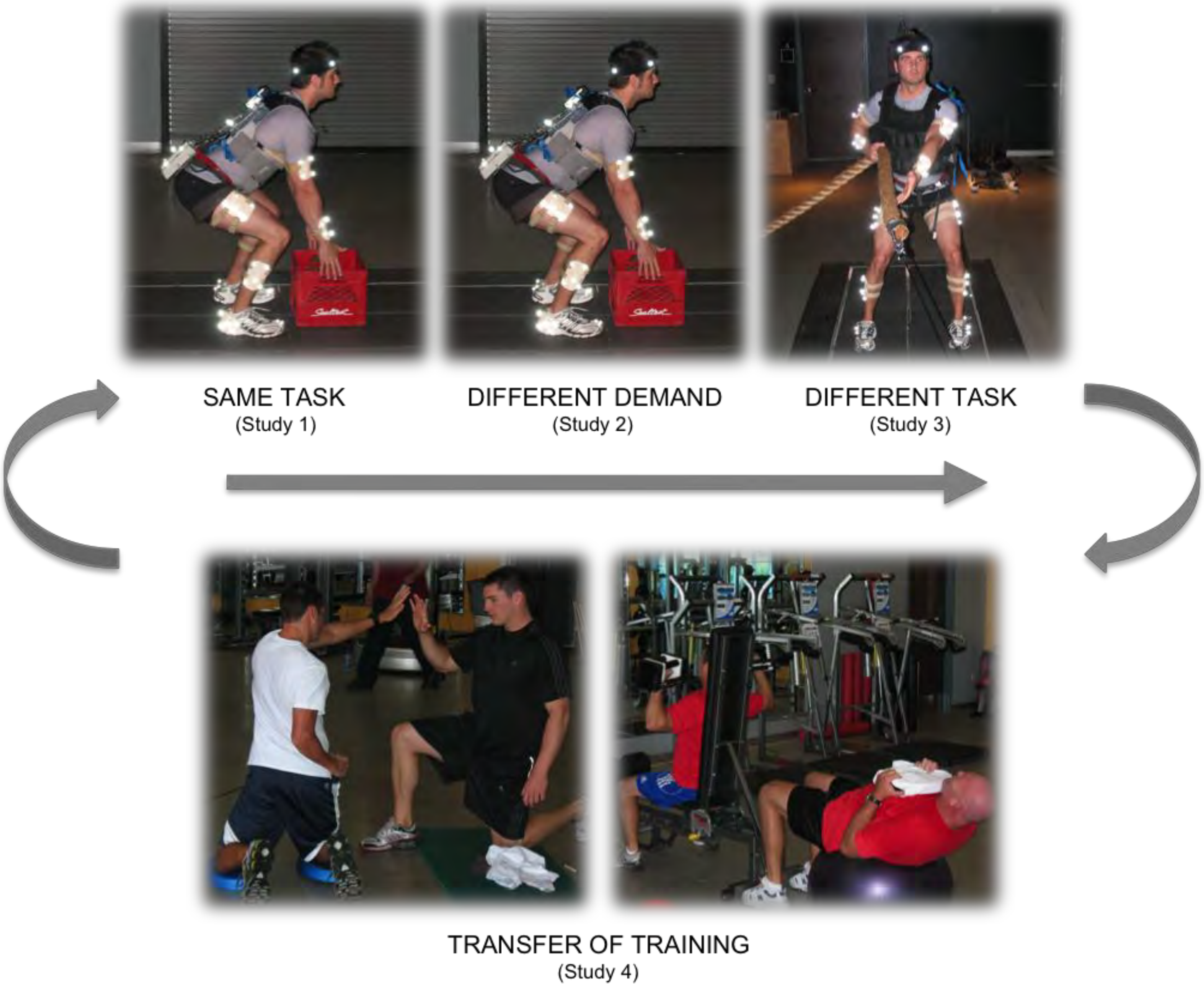


Figure 1.1. This thesis comprised four studies each building on the investigations that preceded it. First, movement pattern variability was examined by having participants perform multiple repetitions of the same task. Second, the same task was performed with varying demands (load and speed). Third, different tasks were contrasted to determine whether an individual's movement patterns could be generalized. The fourth study examined the influence of two 12-week exercise programs (fitness and movement-oriented fitness) on the movement patterns used to perform a battery of general tasks that were not coached or practiced during training.

1.5. RESEARCH QUESTIONS AND HYPOTHESES TESTED

The four studies described above were conducted to investigate specific hypotheses related to the global thesis objectives.

Study 1: Movement variability and the estimation of "meaningful" change

Firefighters' movement patterns were evaluated while they performed two general lifting and two simulated firefighting tasks. The hypotheses tested were that substantial between- and within-subject variation would be observed in the variables used to describe participants' movement patterns, although each would be repeatable between sessions. Secondly, it was anticipated that the participants' variability could be used to develop a means of defining biologically significant or "meaningful" within-subject differences. The within-subject variation may offer a simple means to accommodate the variability displayed amongst and by the participants without having to collect a large number of trials, and therefore, could provide a tremendous opportunity to explore various interventions designed to prevent musculoskeletal injury or improve performance.

Study 2: Load, speed and the evaluation of movement: A task's demands influence the way we move

Firefighters performed five whole-body tasks with varying externals loads and movement speeds. It was hypothesized that individuals would adjust their movement patterns in response to changing the tasks' demands, albeit to varying degrees across participants. If individuals exhibit an adapted movement strategy when the demands of task are modified, the utility of any movement evaluation comprising only low demand activities may have limited application.

Study 3: The predictive value of general movement tasks in assessing occupational task performance

Firefighters' movement patterns were evaluated while they performed a battery of general tasks and occupation-specific skills to simulate the demands of their job. The hypothesis tested was that a battery of general tasks could not be used to describe the movement patterns adopted to perform select job-specific skills. Attempts to generalize the results of a movement evaluation or screen may lead to inaccurate characterizations (e.g. high risk) and inappropriate recommendations for training.

Study 4: Periodized exercise and the transfer of training: Can we change the way an individual moves?

The adaptations (fitness and movement) exhibited by professional firefighters in response to two training methodologies were examined. The hypothesis tested was that a movement-oriented fitness training program, wherein attention was given to *how* each exercise is performed, would elicit a change in participants' movement patterns while they performed a battery of transfer tasks. It was anticipated that the adaptations observed would be dissimilar to those exhibited by firefighters participating in a fitness-oriented training program that emphasized metrics such as strength, muscular endurance and cardiorespiratory efficiency alone. A secondary hypothesis was that the adaptations observed would be individual-specific. Exercise may be an effective tool to change an individual's habitual movement patterns, which for occupational athletes such as firefighters, soldiers and police officers, implies that training could have a direct impact on their safety and effectiveness.

Chapter 2

REVIEW OF LITERATURE

THE PHYSICAL PREPARATION OF FIRE FIGHTERS

2.1. A COSTLY PROBLEM

Firefighting is an unpredictable, high-risk occupation. It is not uncommon for incumbents to find themselves in perilous situations wherein the physical demands of the job exceed their capacity, or ability, to perform in a safe and effective manner. Instances such as battling a live fire, rescuing a victim, or dealing with the unforeseen collapse of a structure each deliver a unique set of demands that may result in an injury to ill-prepared firefighters. In 2008, the rate of non-fatal occupational injury for firefighting ranked second highest amongst all industries (13.4%) (Bureau of Labor Statistics. U.S. Department of Labor, 2009) and was three times that of the United States Labor Force (Riechard and Jackson, 2010).

Over the past thirty years the number of injuries sustained annually by United States firefighters has been reduced by 24% (Karter Jr and Molis, 2010). However, this decreasing trend appears to encompass only those injuries incurred during fireground operations (Figure 2.1); the number of injuries suffered while training, responding to non-fire calls, or attending to other on-duty responsibilities has not changed. And further, the drop off in fireground injuries parallels the decline in the number of fires (Karter Jr and Molis, 2010), thus implying that there has actually been no change in the rate of fireground injuries for thirty years (Figure 2.2). In fact, the incidence of strains and sprains (musculoskeletal injuries), which account for approximately half of all fireground injuries, has doubled since 1981 (Figure 2.2).

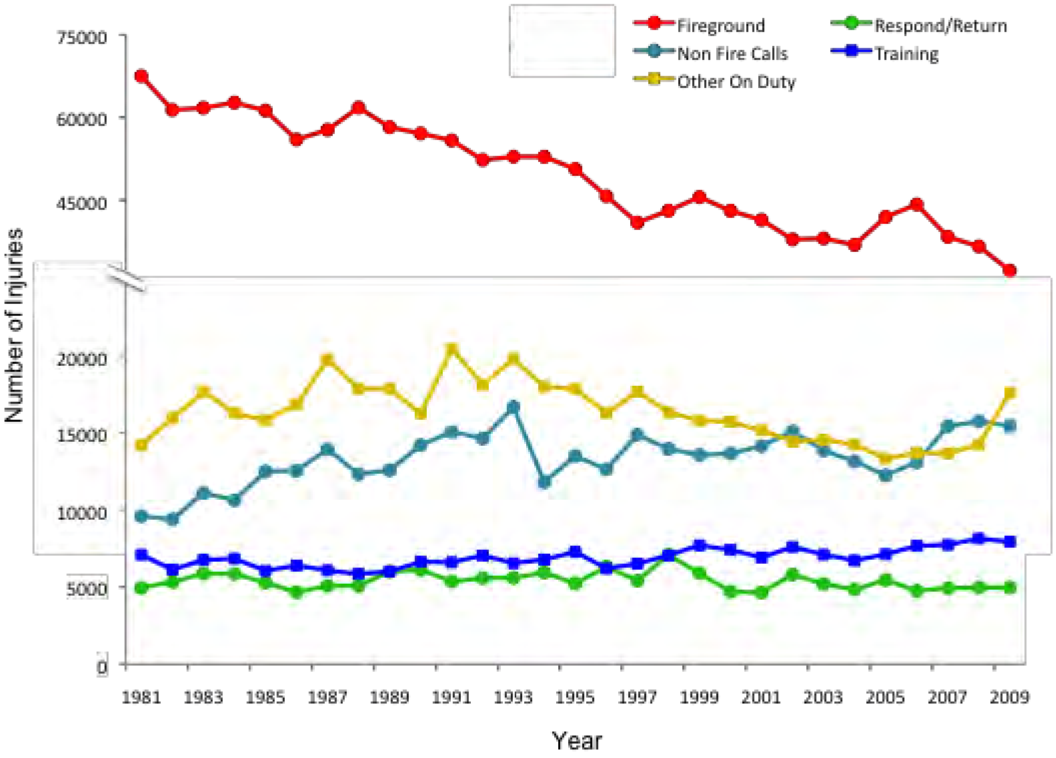


Figure 2.1. Total number of firefighter injuries from 1981 to 2009. Data adapted from the National Fire Protection Association.

Firefighting is and always will be a physically demanding high-risk occupation, and thus all injuries will never be avoided, but the effectiveness of prevention programs may improve if additional efforts are focused on better understanding the leading causes of musculoskeletal injury. Albert (2009) recently reported a three-year, job related injury prevalence of 81% in a mid-size (350 active firefighters) urban department, of which 48% of the injuries were specific to the lower back and 55% were the result of lifting. Similar findings were reported by Walton et al. (2003) upon reviewing the compensation records of 77 municipalities over a six-year period; 42% of all claims were related to the lower back and 48% cited lifting as a primary cause. The National Institute of Standards and

Technology (2004), has estimated that the annual costs (direct and indirect) of addressing firefighter injuries could be as high as $7.8 billion in the United States alone. Of this total, $830-$980 million is spent on prevention in hopes of reducing the substantial human and economic impact of injuries; however the injury trends suggest that a novel framework may be needed that addresses both the mechanisms of injury and the highly variable demands of the occupation.

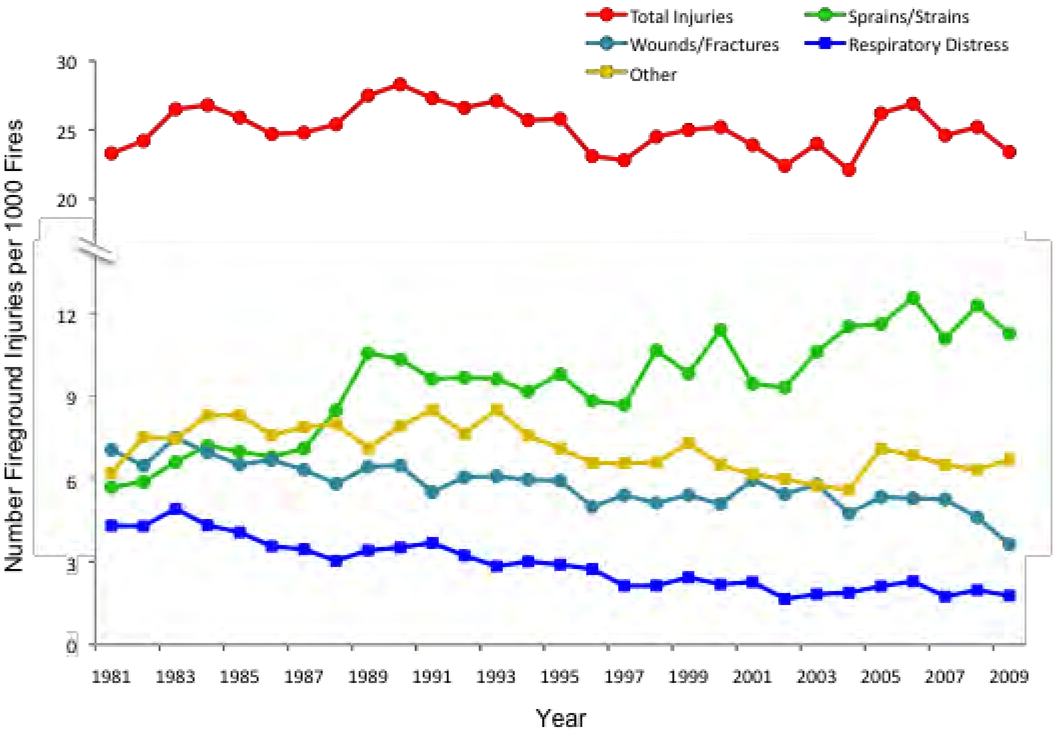


Figure 2.2. Rate of fireground injuries between 1981 and 2009. Data adapted from the National Fire Protection Association.

Every work task can be characterized by the physical demands placed on the cardiovascular and musculoskeletal systems. When sufficient capacity (i.e. ability, awareness and desire to perform safely and effectively) is lacking and the unique job demands cannot be matched appropriately, safety and effectiveness are compromised. This unfortunate situation can increase a firefighter's risk of injury and endanger their co-workers and the people they aim to protect. Reducing the number and severity of musculoskeletal injuries amongst firefighters can therefore be directed in one of two ways:

task-centered or worker-centered, both of which seek to balance job demands and worker capacity.

Task-centered strategies aim to *fit tasks to workers* based on fundamental principles of ergonomics science. The fire service has used this approach with some success by modifying the physical dimensions of equipment or the storage location of tools to reduce the musculoskeletal demands associated with tool use or transport. Such efforts have focused on increasing the "margin of safety" by attenuating task demands without specifically addressing worker capacity – an excellent approach for certain aspects of the job. However, firefighting is highly variable and often unpredictable. Tasks are unconstrained and may be repeated at irregular intervals under different environmental conditions and situational constraints; incumbents must be prepared for the unexpected. Because safe and effective firefighting are heavily influenced by one's physical abilities and preparedness worker-centered interventions may be better suited to impact the incidence of injury within the fire service.

Worker-centered strategies seek to increase the "margin of safety" by improving capacity. Efforts are made to *fit workers to tasks*, or, best prepare firefighters to meet the demands of their occupation. It is difficult however to gauge progress or evaluate the effectiveness of any intervention without first establishing reliable criteria with which to measure capacity, or further, place it into the proper context whereby it can be compared to the musculoskeletal demands of the job. The physiological demands of firefighting have been studied extensively (Elsner and Kolkhorst, 2008, Scheaff, 2009, Williams-Bell et al., 2010, Williams-Bell et al., 2009), but little is known about the demands on the musculoskeletal system. The International Association of Fire Fighters (IAFF) has developed fitness standards for new recruits and compared entrance scores to various measures of strength and endurance, yet the role of fitness remains a topic of much discussion with regards to the prevention of injuries. Cady et al. (1979) found that firefighters with a higher degree of fitness suffered fewer and less costly injuries than their unfit co-workers, however strong evidence from the military literature suggests that fitness-oriented programs may not be an effective strategy to prevent the occurrence of future sprains and strains (Almeida et al., 1999, Jones et al., 1993b). Musculoskeletal injuries occur when discrepancies exist between the demands of a task and the capacity of an individual (albeit at the tissue level); they are a mechanical problem influenced by several factors aside from fitness, each of which needs to be understood before devising appropriate physical preparation (injury prevention and performance) strategies for firefighters.

2.1.1. The Role of Fitness

Given the physical demands of an occupation such as firefighting, general fitness (e.g. strength, endurance, aerobic capacity) is often viewed as critical to one's preparedness. In fact, recruitment standards have been created to prevent the hiring of individuals who lack the physical abilities deemed necessary to fight fires and exercise guidelines are now provided to all incumbents (International Association of Fire Fighters). However, firefighters still become injured (as do soldiers, police officers and other athletic populations); and in many situations the injuries incurred are the direct result of efforts to become better physically prepared (Almeida et al., 1999, Jones et al., 1993b, Knapik et al., 2001, Poplin et al., 2012). This unfortunate reality has created many challenges, both personally and for the profession, but it has also inspired a great deal of fitness and occupation-specific research directed at better understanding the relationship between fitness and injury and the influence of training (i.e. improving capacity) on one's safety and effectiveness.

Muscular strength (Knapik et al., 1991, McGill et al., 2003), endurance (Beiring-Sorensen, 1984, Jones et al., 1993b, Knapik et al., 2001, McGill et al., 2003), aerobic capacity (Jones et al., 1993a, Jones et al., 1993b, Knapik et al., 2001) and flexibility/joint range of motion (Bradley and Portas, 2007, Jones et al., 1993b, Knapik et al., 1991, Knapik et al., 2001, Witvrouw et al., 2003) have each been cited as risk factors for injury (or joint troubles), thus making it logical to assume that these same variables should be a point of emphasis when training to improve job readiness. But, do these tests provide an accurate representation of worker capacity, particularly, when placed into context and compared to the musculoskeletal demands of one's job? Furthermore, what is the mechanism by which a flexibility intervention, for example, might prevent future injury? Interestingly, Hilyer et al. (1990) posed this same question, but found that it could not. Improving overall flexibility in a cohort of firefighters (six-month intervention) was unable to reduce the incidence of injury in the two years following the investigation. Similarly, “plyometric” and “core strengthening” programs designed to improve various components of fitness have been unable to reduce the incidence of ACL injury (Pfeiffer et al., 2006) and back pain (Nadler et al., 2002), respectively. Perhaps fitness tests simply provide insight into the status of a person’s capacity to perform on that specific test. Further interpretations may require caution so as to not infer causation and misdirect one’s physical preparation efforts towards improving the test. There is clearly a relationship between job performance, injury risk and fitness, however training to achieve an arbitrary standard may have little impact on anything but the test itself.

Being physically fit, in the traditional sense, may not equate to being physically prepared for the demands of one’s job. Particularly given that confounding factors can influence the expression of strength, endurance or range of motion, thereby limiting their direct impact on the incidence or prevention of injury. Fitness is essential, particularly for firefighters, but alone it is not sufficient to ensure peak performance and long-term durability; it simply reflects an individual’s potential capacity. For example, poor torso extensor endurance has been cited as a marker for future low back troubles in men (Beiring-Sorensen, 1984), although it is not one of the most commonly described mechanisms of low back injury (e.g. spine posture and joint compression and shear (Callaghan and McGill, 2001, Howarth, 2011)). A rational explanation is that superior endurance provides the opportunity to maintain spine-sparing postures (and reduced joint loads) for extended periods of time by delaying the onset of fatigue. However, if individuals cannot (or choose not to) adopt these postures for any number of reasons, muscular endurance becomes secondary and will have little bearing on the risk of injury. Great fitness in the absence of poor mechanics or great mechanics in the presence of poor fitness will limit performance and increase one’s chances of sustaining a musculoskeletal injury. Both scenarios reflect the undesirable state where a firefighter’s demands will exceed their capacity.

In developing a framework to physically prepare firefighters, fitness might be best viewed as a means to support the musculoskeletal (movement) system. Firefighters must be sufficiently “fit” to perform their work tasks in a safe and effective manner, yet it could be argued that both objectives are influenced to a greater degree by an individual’s movement patterns. Consider the firefighter with excellent joint range of motion and great body awareness, but poor muscular strength. He/she may have the ability (capacity) to perform safely and effectively when the task demands are low (i.e. minimal strength or anaerobic capacity required), but frequently become injured while at the scene of a fire. When faced with the elevated demands of a call, and muscular strength and cardiovascular ability are critical to the preservation of “proper” mechanics, this individual lacks the fitness to do so; they are not *fit to move* in a manner whereby their capacity matches the demands of the task. A similar outcome is likely for the firefighter who has focused his/her efforts on improving muscular strength only. He/she may lack the flexibility, endurance or awareness to move in a manner that promotes safe or effective firefighting, and thus might need to emphasis other aspects of “fitness” in order to avoid future injury during the performance of any task. These fictional scenarios assist to place the traditional perception of fitness into the demands and capacity framework, but also highlight the need to better understand the relationship between movement patterns and injury. As stated previously, injuries occur when the capacity of a tissue (tolerance) is exceeded by the demands placed upon it (applied load), and interestingly, both capacity and demands are modulated by the way an individual moves.

2.1.2. The Role of Movement

An individual’s movement patterns are a reflection of the neuromuscular strategies used to perform any physical task. Frequently modified (either voluntarily or involuntarily) in response to perceived demands or through knowledge gained from previous experiences, they can make challenging tasks very simple or turn seemingly mundane chores into injury-causing events (by influencing demands and/or capacity); the outcome will depend on the strategy chosen. For example, when bending forwards to pick up a heavy object (e.g. a charged hose) an individual can flex entirely from the spine or the hips or they can adopt a strategy that combines motion from both joints. However, their decision will have a significant impact on the muscle groups involved (McGill et al., 2000), distribution of tissue loads (muscle versus passive tissue) (McGill, 1988) and risk of injury.

Adopting a flexed spine posture changes the orientation of the lumbar extensor musculature (McGill et al., 2000), thereby compromising its ability to resist the shear loads (a risk factor (Norman et al., 1998)) imposed on the back by gravity while lifting. Repeated bending of this nature is also a mechanism for disc herniation (Callaghan and McGill, 2001), exacerbated by increasing the magnitude of joint compression (e.g. load in hands). Does this imply that all spine flexion should be avoided? No; and to the author's knowledge there is no prospective evidence to suggest that the incidence of injury in the workplace can be reduced by efforts to modify lifting technique or low back postures. However, the way individuals move does impact joint loading (Hewett et al., 2005, Kernozek et al., 2006, Koyanagi et al., 2006, Lenaerts et al., 2009) and several motion-related variables have been cited as risk factors for injury (Hewett et al., 2005, Ludewig and Cook, 2000, Marras et al., 1993, McGill et al., 2003, Norman et al., 1998, Pohl et al., 2008). Consequently, placed into the appropriate context, an individual's movement patterns may offer a biomechanical justification as to why an injury was sustained or more importantly, provide the foundation from which to guide future injury prevention research and practice.

In 1996, motivated to better understand why female athletes suffer more knee injuries than their male counterparts, Hewett and colleagues conducted one of the first investigations to examine the mechanics of jumping and landing before and after training (Hewett et al., 1996). Marked differences were noted between genders prior to the intervention, but with training the female athletes were able to improve their hamstring to quadriceps strength ratios (post values were not different than males) and reduce their peak landing forces and knee adduction/abduction moments by 22% and 50%, respectively. These findings provided a biomechanical rationale as to why gender differences might exist. Three years later, the same group conducted a second study to prospectively evaluate the effect of their "neuromuscular" training program on the incidence of knee injury in females (Hewett et al., 1999). Over twelve hundred high school athletes were recruited; they were then separated into three groups (trained and untrained girls and untrained boys) and monitored over the course of one sport season. The training group (n=366) received instructions regarding jumping and landing technique and was required to complete a 6-week program (60-90 minute sessions, 3 times per week) before their season began. Untrained female athletes were 3.6 and 4.8 times more likely to sustain a knee injury than trained females and untrained males, respectively; and interestingly, the incidence of knee injury amongst the females who completed training was not different than the group of untrained boys (p=0.86).

Training was able to alter jump/landing mechanics (Hewett et al., 1996) and reduce the incidence of knee injury (Hewett et al., 1999), thereby providing support for the notion that the way an individual moves could be an indicator of risk. At least Hewett's group thought so (Hewett et al., 2005). They hypothesized that a female's risk of anterior cruciate ligament (ACL) injury could be predicted by examining her lower extremity mechanics during a jump-landing task. In a second prospective study (Hewett et al., 2005), female athletes were screened (3D kinematics and kinetics) and then monitored throughout their competitive seasons. Of the 205 participants, 9 sustained a confirmed ACL rupture. The pre-participation screen showed that injured athletes displayed significantly higher knee abduction angles (8°), knee abduction moments (2.5 times) and ground reaction forces (20%) at landing, in comparison to the non-injured females. Knee motion and loading were in fact able to predict ACL injury risk with a high degree of sensitivity and specificity (Figure 2.3).

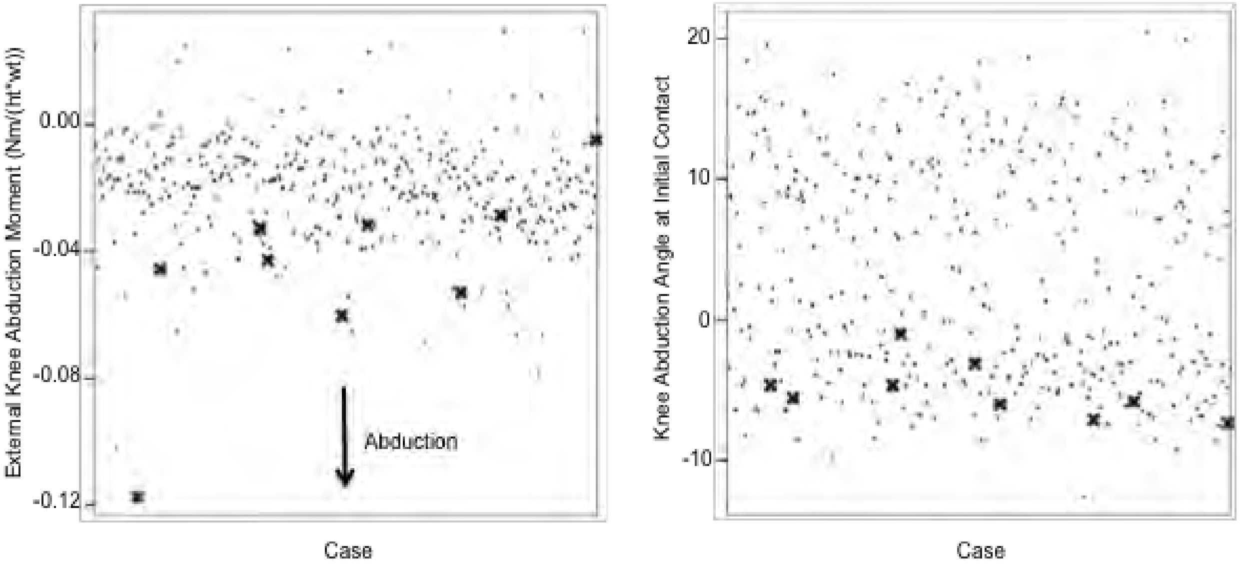


Figure 2.3. Scattergram of peak knee abduction moment and knee abduction angle at initial contact in injured (X) and uninjured female athletes (ht – height, wt – weight). Data adapted from Hewett et al. (2005).

Research efforts such as those described above have helped to establish a relationship between movement patterns, tissue loads and the consequent risk of injury. Scientists and practitioners are now trying to better understand how exercise, coaching or feedback can be used to influence the movement strategies chosen to perform a variety of tasks (DiStefano et al., 2009, Herman et al., 2009, Herman et al., 2008, Kernozek et al., 2006, Lavender et al., 2007, Myer et al., 2006, Noehren et al., 2011). For example, movement-centered feedback has been tested as a means to reduce joint loading (Kernozek et al., 2006) and the incidence of injury (Lavender et al., 2007) while lifting and lowering and to alleviate chronic knee pain while running (Noehren et al., 2011). Typically, however, researchers will use well-described injury mechanisms to define the specific kinematic and kinetic parameters they wish to change (e.g. knee abduction angle, knee abduction moment) and injury-causing events (e.g. jump-landing) to evaluate them; an evidence-driven approach shown to be effective for many populations; firefighting not included. The unpredictable, unconstrained nature of the occupation prevents such an approach from being easily adapted, in large part because the demands on the musculoskeletal system have not yet been well described. As a result, it is difficult to identify and evaluate the job-tasks most relevant to injury, and more importantly, to substantiate the description of a particular movement pattern as “good” or “bad”; which in turn can also complicate the design of an intervention, the data collection/processing procedures and the interpretation of any findings.

General principles (e.g. individuals should seek motion at the hips instead of the lumbar spine) may assist to guide the selection of parameters with which to categorize and evaluate a firefighter’s movement patterns. Likewise, the screening of general tasks (e.g. squat or box lift) may provide a simple means to assess a firefighter’s relative risk of injury without having to simulate an unconstrained, potentially injurious event. However, essential to such an approach is an appreciation for movement variation and task specificity. Movement is inherently variable (James and Bates, 1997), influenced by factors such as perceived risk, prior experience, whole-body coordination and strength, and thus an individual’s adopted pattern (voluntary or involuntary) will likely be task and demand specific. As a result, it may be important to place tasks into context when evaluating the parameters selected to describe motion. Simply because an individual exhibits a particular pattern (perceived to be good or bad), does not mean that they have to (they may have ability) or that they will perform in a similar manner if asked to perform another task comprising different demands. Additional research is needed to investigate the degree to which motion characteristics are modified across conditions (tasks and demands) and influenced by various factors, so that as a scientific community we can better interpret their utility in predicting injury or guiding the design of an intervention. Fundamental to understanding the role of movement and its application to the overall physical preparation of firefighters is an appreciation for movement itself.

2.2. A WORKER-CENTERED APPROACH TO PREPARATION

Continuous variation in the neuromuscular and skeletal systems and subtle changes to the external environment prevent the exact repetition of any movement pattern (Hatze, 1986), thereby making the performance of a particular motor task unique to that individual at that moment (James and Bates, 1997). Movement variability may reflect an inherent adaptive response or protective mechanism to minimize the accumulation of tissue damage that might occur when the same task is repeated numerous times (Bartlett et al., 2007), or alternatively, an ability to coordinate and control one's body in space. Bernstein (1967) considered variability to be an outcome of motor learning. He provided the framework for an entire field of study when he theorized that improved coordination was associated with the mastering of redundant mechanical degrees of freedom (DOF), such that as an individual becomes more familiar with a task they gradually remove (subconsciously or consciously) all restrictions on the DOF, thus allowing greater variation in a movement pattern. However, researchers have since argued that such a hypothesis might be constraint and task dependent (Newell and Vaillancourt, 2001). Novice performers may gradually release rigid control of the their movement systems as they become more familiar with certain tasks (e.g. ski simulation (Vereijken et al., 1992)), but exhibit greater variation in comparison to skilled participants while performing others (e.g. bouncing a ball (Broderick and Newell, 1999)). Given that every movement pattern arises from the cooperation of many different muscles acting as synergists (Carroll et al., 2001), each contributing to the forces and moments at joints other than those they span (Zajac, 1989), attempts to generalize across tasks and/or individuals are likely inappropriate and may skew the methodological design of an investigation or the interpretation of any findings.

Many investigations use a unique set of descriptors to characterize the movement pattern(s) studied. Specific variables are chosen to reflect joint angles, joint moments or the coupling of multiple segments, for example, and conclusions are made regarding task performance. It is difficult however to ensure that the chosen descriptors capture the most important elements of a pattern, particularly when investigating a task with few external constraints (e.g. firefighter simulated hose drag). Consequently, any findings pertaining to "movement" variability or the influence of a particular intervention may be specific to the descriptors chosen to represent that pattern; which is entirely appropriate if generalizations are limited. Further, individual variation must be considered, and perhaps even more so within a physically demanding occupation such as firefighting. Every individual will not perform the same task in a similar manner, nor will they respond to varying tasks or task demands with the same adapted behaviour (Caster and Bates, 1995). Therefore, fundamental to the establishment a worker-centered approach to injury prevention or physical preparation is the evaluation and enhancement of capacity.

2.2.1. Evaluating Capacity

Describing an individual's capacity is essential for the development of long-term sustainable physical preparation strategies for firefighters. Being fit in the traditional sense (e.g. strength and endurance) does impact a firefighter's capacity and thus needs to be evaluated to guide the prescription of exercise, but as stated previously, in the absence of sound movement patterns it simply reflects potential. Many researchers have investigated the physical requirements of firefighting and made recommendations towards improving fitness (Adams et al., 1986, Findley et al., 1995, Michaelides et al., 2011, Roberts et al., 2002, Williams-Bell et al., 2010, Williams-Bell et al., 2009), but to the author's knowledge no one has considered the relationship between capacity and movement. Therefore, the discussion to follow will be focused on the evaluation movement within the context of describing an individual's capacity.

Describing Motion

ACL injury prevention researchers have been able to change movement patterns (Hewett et al., 1996, Noyes et al., 2005), attenuate joint loading (Hewett et al., 1996, Myer et al., 2007) and reduce the incidence of injury (Hewett et al., 1999, Mandelbaum et al., 2005) by contrasting the movement patterns employed during non-contact ACL injury events to ACL loading mechanisms. However, it is not possible to characterize the culminating event for most injuries, nor is it appropriate to describe all movement patterns with a select group of discrete variables. Quantifying movement strategies can therefore be an extremely difficult task, particularly when the body is appropriately viewed as a series of interconnected segments. Restricting the analyses to one area (e.g. knee) can simplify the experimental design, which might be appropriate for certain investigations, but it may also conceal potentially relevant information. Davis and Seol (2005) found that injured segments distal to the trunk (i.e. foot and ankle) could significantly influence trunk kinematics. The presence of joint mobility- or control-limiting factors (e.g. strength, range or motion, motor control) at any location throughout the kinematic linkage can influence the movement strategies employed by affected individuals, and thus it might be of benefit to assess the coordination of or relationship between multiple segments and joints.

Given the success of ACL researchers and the relationship between movement patterns, injury and performance, scientists and practitioners have begun using whole-body movement screens to expose “faulty” or “aberrant” patterns that might predispose individuals to any injury (Cook et al., 2006a, Harris-Hayes and Van Dillen, 2009, Kritz et al., 2009a, Mottram and Comerford, 2008, Plisky et al., 2006). Several groups have chosen to use qualitative criteria to describe their select tasks, making their evaluations simple and time-efficient; however, to the author’s knowledge, every published whole-body screen (qualitative or quantitative) comprises an evaluation of those patterns used to perform low-demand tasks (e.g. bodyweight squat), and thus may not provide an accurate view of an individual’s capacity as it relates to their life’s (job’s) demands. As a result, several potential challenges must be considered. First, it is difficult to interpret the relevance of the various screening tasks used, particularly considering the lack of evidence regarding the transfer of learning. Knee kinematics and kinetics measured during drop jumps may provide information related to ACL injury risk, but do not necessarily yield direct information pertaining to the risk of suffering other common musculoskeletal injuries associated with a broad range of occupational activities; nor do we understand the degree to which task specificity exists (i.e. are there patterns common to various tasks?). A second challenge, relevant to any screen, is that the way individuals perform a given task can be influenced by a number of factors including coaching and feedback (Cowling et al., 2003, Dempsey et al., 2009, Herman et al., 2009, McNair et al., 2000, Onate et al., 2005). It may therefore be difficult to establish reliable criteria by which to rank movement quality over multiple testing sessions. Lastly, clear distinctions must be made between what individuals *can* do (i.e. movement abilities) and what they *choose* to do (i.e. habitual movement strategies). Just because an individual *can* perform a particular task in a certain way (given specific instructions in a controlled setting) does not mean they *will* perform in a similar manner when faced with an elevated task demand (e.g. load) or in the unpredictable environment of their occupation.

Each of the abovementioned challenges complicates the description of movement by placing the screening tasks chosen or the individual's capacity and demands into context; they highlight several factors that can influence the way someone moves. There are however, additional difficulties that may arise when deciding on the specific variables with which to describe motion. Discrete kinematic and kinetic variables are often used to represent an individual's motion characteristics and corresponding joint forces and moments, respectively, and can be presented as a trial mean or referenced to a specific event or instant in time. Descriptions of this nature can provide valuable detail regarding the critical elements of any pattern, although some researchers have chosen alternative approaches in fear that they would miss potentially relevant information (O'Connor 2009). To capture the temporal characteristics of a pattern or the sequencing of multiple segments/joints, one could analyze the data with time-series plots, relative motion plots (joint angle-joint angle (Wilson et al., 2008)), relative phase plots (segment motion-joint motion (Hamill et al., 1999)) or cross correlations (Stergiou, 2004), for example, but each is also difficult to evaluate in terms of the magnitude of inter- and intra-individual differences. It can therefore be very challenging to assess the influence of various interventions on the movement patterns used to perform a given task. Various statistical procedures, such as Principal Components Analysis (e.g. O'Connor 2009) and Factorial Hidden Markov Models (Kulic et al., 2009), have been adopted to characterize motion and detect general changes, but the results do not have intuitive meaning and thus their practical application may be limited. Every approach comprises advantages and disadvantages that may make it more suitable to investigate a specific research question; however, fundamental to any investigation involving human movement should be an appreciation of the possibility of inter- and intra-individual variability (Hopkins, 2000).

Individual Variation

Any scientist or practitioner involved with injury prevention, rehabilitation or performance enhancement will appreciate the significance of individual variability. Each of us is unique, both in the way we approach the execution of specific tasks (Morriss et al., 1997, Rodano and Squadrone, 2002) and the manner in which we respond to various interventions (Caster and Bates, 1995, Dufek and Bates, 1990, Dufek et al., 1995); what is beneficial for some may be entirely inappropriate for others. However, large randomized controlled studies are often viewed as essential to the generalization of findings, despite evidence to suggest that a group's response may simply reflect a "mythical average performer" and few, if any, of the actual participants in the investigation (Caster and Bates, 1995, Dufek and Bates, 1990, Dufek et al., 1995). For example, Dufek et al. (1995) evaluated the lower extremity response to variations in stride length (normal, over-stride and under-stride) with group and single subject-analyses, and found that although 94.4% (17 of 18) of the subject-condition interactions were significant, none of the individuals performed using the group's strategy. Inter-subject variation, and not large sample sizes, may be essential to extending generality because it can threaten external validity and impact the interpretation of any findings (James and Bates, 1997).

Understanding the degree to which a specific pattern or movement descriptor may vary across a population will undoubtedly assist with the development of effective worker-centered interventions; however, efforts must also be made to estimate the inter-trial repeatability for each dependent measure used in a given investigation. Describing the motion characteristics of a certain task without acknowledging or accounting for the potential within-subject variation may drastically skew the conclusions made and lead to false support for the null hypothesis. Generally, collecting several trials is viewed as good scientific practice and thought to provide more stable measures and a better representation of an individual's movement patterns (Bates et al., 1983). Too few trials can be problematic if the magnitude of variation falls inside that which is typical for the specific measures being presented. Single trial experimental designs may be unreliable and inappropriate for human movement research because one must assume that variability is negligible (Bates et al., 1992). Each trial must represent the typical performance of every participant in the investigation, which is highly unlikely outside of chance.

The minimum number of trials necessary to achieve stable estimates for dependent variables measured during running (Bates et al., 1983, DeVita and Bates, 1988), walking (Hamill and McNiven, 1990), vertical jumping (Rodano and Squadrone, 2002), lifting (Dunk et al., 2005), drop landing (James et al., 2007) and cricket bowling (Stuelcken and Sinclair, 2009) has been reported to be in the range of 4 to 20 using sequential averaging (SEQ). A statistical procedure that involves calculating the cumulative means and mean deviations for each successive trial collected (James et al., 2007). Stability is achieved when the cumulative mean is within a specified range (e.g. 0.25 SD) of the total trial mean. SEQ has been shown to offer a more conservative prediction of stability than a traditional test such as the intra-class correlation coefficient (ICC) (James et al., 2007), although its estimation is dependent upon the arbitrary selection of an acceptable deviation (e.g. 0.25 SD) and the total number of trials collected (DeVita and Bates, 1988). With slight modifications to either parameter the estimates of the SEQ do closely resemble those of the ICC (James et al., 2007), thus the decision to use one test versus another will likely depend on the specific research questions being investigated. Efforts to establish reliable criteria with which to describe a particular pattern may require more conservative estimates of inter-trial variation than those seeking to define boundaries for an intervention, outside of which can be defined as a biologically significant or "meaningful" adaptation or change.

Task Demands

Thus far much of the discussion surrounding the evaluation of movement has been focused on the description of a pattern and the possible variation within or between individuals, despite the fact that the physical preparation of firefighters (or anyone for that matter) would seemingly require that such factors be considered while observing an individual perform various tasks that are relevant to their demands. Evaluating an individual's capacity (and perhaps their movement patterns) requires context. If the demands of the evaluation do not adequately reflect the most challenging (or potentially injurious) tasks performed on a daily basis, any information collected may have limited application. For example, using an unloaded lifting task to assess a firefighter's risk of sustaining a lifting-related occupational injury may not be appropriate if the typical mechanism for injury involves high external loads. Injuries occur when demands exceed capacity, and quite often it is the demands of a task and not the task itself that evokes the movement patterns, or uncontrolled motions that create problems (Kulas et al., 2010, Van Dillen et al., 2008).

Dufek et al. (1995) proposed that the way an individual responds to varying demands ranges along a continuum from total accommodation to complete dismissal. The group theorized that the strategy chosen to perform a given task would depend on the recognition of the demands and the perceived severity of its potential effects on the body. Although the primary basis for such an assertion was previous work documenting individual variation in impact forces during running (Bates et al., 1988, Bates et al., 1983) and landing (Caster and Bates, 1995, Dufek and Bates, 1990), a similar framework may be applicable to the study of movement patterns (i.e. kinematics). When presented with two tasks of the same pattern (e.g. lifting) but different demands (e.g. heavy versus light load), some individuals will perform both with a very similar movement strategy; others however, will adapt their movement behaviour and exhibit varying degrees of task demand dependence. For example, Flanagan and Salem (2008) found that amongst participants, a range of movement strategies were used to perform a squat, but interestingly, convergence was noted as the load increased from 25% to 100% of the three-repetition maximum. Although no mention was made to the variation amongst participants, McKean et al. (2010) also found that increasing the barbell load had a significant impact on the magnitude of hip and knee flexion used while squatting.

The degree to which a movement strategy is altered in response to an increased/decreased task demand may depend in part on the perception of risk as was suggested by Dufek et al. (1995); however, additional factors such as awareness, coordination and fitness (e.g. strength) may be equally important. Speculating as to the exact reason why a pattern is changed would therefore be very difficult, particularly given the lack of evidence to support a homogeneous response. Faced with the task of picking up a pencil off the floor, highly astute, physically capable firefighters may not choose to adopt the same strategy that they would use to lift a heavy piece of equipment if their perception of the pencil task was such that it could not cause harm. On the other hand, highly astute firefighters with poor fitness may exhibit similar patterns for both tasks because they lack the strength necessary to perform the heavy lift in such a manner that would be viewed as "safe" or "good"; the demands of the task exceed their capacity to perform in a safe and effective manner. Using a similar argument, Savelberg et al. (2007) hypothesized that the age-related movement strategy differences noted previously (Papa and Cappozzo, 2000), may be partially explained by the load (demand)/capacity ratio. The authors manipulated the effort required (demand) to rise from a chair by applying various loads to the trunk (0-45% body mass) and found that a 45% load increased trunk flexion and the hip extension moment and extended the total movement time. This work provides excellent insight into the extent to which the execution of a functional task like rising from a chair can be altered by elevating the task demands. However, perhaps even more valuable is the finding that the response appears comparable to that of an elderly population (lower capacity) who were asked to perform a less demanding (unloaded) variation of the same task (Papa and Cappozzo, 2000). It appears that individuals adapt their movement patterns in response to changes in the relationship between their demands and capacity.

Without a framework with which to describe a pattern as "good" or "bad", the way an individual responds to varying demands could arguably be viewed as secondary to simply acknowledging the fact that their movement patterns might be context (demand) specific. Whole-body movement screens are frequently used to assess one's ability to perform various general patterns (e.g. squat, lunge) (Goss et al., 2009, Kiesel et al., 2007, Kiesel et al., 2010, Kritz et al., 2009a, Kritz et al., 2009b, Kritz et al., 2010, Mottram and Comerford, 2008, Peate et al., 2007), yet little consideration is ever given to the possibility that a task's demands may influence the way an individual moves. The screens typically comprise bodyweight patterns and individuals are instructed to perform in a slow, controlled manner, irrespective of the population being tested or the long-term rationale behind the evaluation. For example, the Functional Movement Screen™, a seven-task test created to evaluate joint mobility and stability (Cook et al., 2006a, Cook et al., 2006b), has been used as a means to predict injuries in athletes (Hoover et al., 2008, Kiesel et al., 2007, Schweim, 2009) and firefighters (Burton, 2006, Peate et al., 2007) and to guide recommendations for training (Goss et al., 2009, Kiesel et al., 2011), despite the fact that its tasks' demands may not provoke the adapted movement patterns that have been linked to the athletic or occupational injuries of interest. That said, there might be tremendous value in a screen of this nature if future research is able to show that the motions exposed during an injury-causing event are not task demand dependent. Until such time, it is recommended that discretion be used when interpreting or generalizing the findings from any movement-based evaluation wherein the individual being examined may vary their movement strategy in response to a change in the screening tasks' demands.

Task Specificity

With respect to the evaluation of movement, task specificity implies that an individual's performance on one task cannot be used to describe their execution of another (Baker et al., 1994). Attempts to generalize may lead to inaccurate characterizations (e.g. high risk) and inappropriate recommendations for training. Given that our perceptions and previous experiences influence the way we move (Dufek et al., 1995) it is difficult to argue against the notion of specificity, but rarely, in the context of evaluating movement, is it even considered. Efforts are made to establish individuals' overall risk of injury using whole-body screens comprising non-specific patterns (e.g. squat, lunge) (Kiesel et al., 2007, Mottram and Comerford, 2008, Peate et al., 2007) that may not reflect those tasks most likely to cause injury in one's life (job). Musculoskeletal injuries account for approximately half of all fireground injuries sustained by firefighters (Karter Jr and Molis, 2010), but to date there is no evidence to suggest that the movement strategies used to execute any of the complex job-specific skills can be captured with a general pattern. There is also no evidence to the contrary.

Although very little is known about task specificity as it relates to movement, many researchers have suggested that an individual's performance (e.g. strength) on two seemingly similar exercises may not be related (Baker, 1996, Baker et al., 1994, Blazevich et al., 2002, Carlock et al., 2004, Cotterman et al., 2005). For example, correlations of 0.55 and 0.11 were reported between the squat and the hack squat (machine-based exercise) (Blazevich et al., 2002) and vertical jump (Baker, 1996), respectively, which led the authors to state that movement pattern specificity should be considered when testing. These findings cannot be used as direct evidence to support specificity of movement, but they do provide a rationale as to why one might question the efficacy of generalizations. That said, gauging an individual's ability to coordinate their body in space with performance metrics (e.g. strength) might be inappropriate; amongst individuals with no reported history of movement instruction, performance and movement appear to be independent attributes (Burton, 2006, Frost et al., 2012a, Okada et al., 2011).

In an ideal world, an individual's capacity would be evaluated within the context of their life's demands. Firefighters would be observed while performing job-specific skills such as pulling hose, forcing entry or extricating victims from a building, and movement strategies would be quantified and used in combination with well-described injury mechanisms to estimate risk. But this type of approach is not always possible (given limited resources) or practical and thus generalizing to some degree might be necessary amongst certain populations. In the event that a specific task is identified as high-risk within a particular demographic (e.g. jump landing in women) and there are well-described injury mechanisms with which to compare individuals' movement strategies, the specific task should arguably be included in all future evaluations for that population. Researchers have been able to predict who will sustain an anterior cruciate ligament (ACL) injury, in part, by evaluating individuals' movement patterns during the performance of injury-causing tasks (Hewett et al., 2005). However, most researchers and practitioners do not consider task specificity and continue to use general (non-specific) tasks to categorize and describe movement competency. There may be merit in using such an approach, though in the absence of a scientific basis the application of any findings might be limited. Additional research is needed to determine the degree to which general tasks can be used to describe the movement strategies adopted to perform the job-specific skills required of a worker.

2.2.2. Enhancing Capacity

Periodized exercise programs and well-designed feedback protocols work – they can (and should) be used to improve capacity. Whether targeting fitness (e.g. strength) on a specific test or the kinematics of a task, most interventions are able to elicit changes in the direction hypothesized by the researchers to be of benefit. For example, scientists have been able to reduce the knee abduction moment in females performing a drop jump (Myer et al., 2007, Myer et al., 2006), alleviate patellofemoral pain in runners (Noehren et al., 2011), lower spinal moments during lifting (Kernozek et al., 2006) and improve performance in weightlifting exercises such as the clean (Rucci and Tomporowski, 2010) and snatch (Winchester et al., 2009). Interestingly however, the effectiveness of fitness-oriented interventions (i.e. no movement-based instruction/feedback) may be limited. Recent evidence suggests that improving strength (Herman et al., 2008, McGinn, 2004) and joint range of motion (Moreside, 2010, Yuktasir and Kaya, 2009) in isolation has minimal influence on the way individuals move while performing whole-body tasks. Even more intriguing (or concerning, depending on your perspective), is the possibility that changes in a movement strategy, when they do take place, might be task-specific. Noehren et al. (2011) used real-time kinematic feedback (eight sessions) to reduce hip adduction and contralateral pelvic drop while running, but found that there was no significant changes to a “transfer task” (i.e. single leg squat) thought to reflect the movement pattern used during the first half of stance.

Enhancing a firefighter’s capacity to match the demands of their job is paramount to their physical preparation. But firefighters, like police officers, soldiers or athletes, are also exposed to unpredictable high-risk environments that cannot be simulated in a gym or evaluated in a laboratory setting, thereby making it impossible to provide task-specific feedback for every situation. Improving an individual’s fitness or altering their movement patterns should be intended to elicit life-related change, which highlights the need to better understand the transfer of training.

The Transfer of Training

Exercise is a tool that we can all use to enhance capacity. It can be used to make difficult tasks easier and more enjoyable; it can be used to prevent musculoskeletal injuries and pain; and it can allow us to perform at levels that far exceed any expectations that we have for ourselves, particularly if it influences the execution of non-exercise related tasks (Carroll et al., 2001). Not every training intervention (exercise or feedback) needs to be designed with these intentions, but when investigating the prevention of injuries or the physical preparation of an occupational group such as firefighters the notion of transference must be considered. Too often assumptions are made regarding the generality of an adaptation simply because the newly acquired skill/movement strategy appears to be similar to that used to perform a job-related task. Developing coordination (ultimately what we are trying to do) is not a simple process. The adaptations demonstrated by each individual will be influenced by their prior experience, inherent structural and functional attributes and personal objectives, not to mention the characteristics of each task being learned (Caillou et al., 2002). It will therefore be important to carefully consider the design and implementation of any intervention being used to effect life-related change.

It has been suggested that to ensure movement specificity and the transfer of training exercises be prescribed that replicate the tasks of interest (Bartlett et al., 2007). For firefighters, this would imply that various high-risk, physically demanding job-tasks be simulated in a gym setting. Although such an approach might seem logical, it is unlikely to afford the most favorable adaptations – enhancing capacity to match the demands of one's job (life) cannot be accomplished by simply prescribing a group of specific exercises. Feedback and coaching are essential to guarantee that the movement strategies being used are safe and effective and, in some environments, may actually have a greater influence on the transfer of training than the exercise itself (Swinnen et al., 1997). The fireground is almost certainly not one of those settings. The physical demands are of such magnitude and variety that fitness will likely be an essential component of any training program designed to prepare firefighters. Movement-based feedback protocols may improve the way that incumbents perform menial tasks, but will prove to be ineffective when the challenges are increased and further capacity is required. Herman et al. (2009) suggested that using a combination of strength training and feedback may offer the greatest opportunity for adaptation, although it should be noted that the investigation was designed specifically to alter various kinematic measures associated with landing and the risk of anterior cruciate ligament injury. The design and implementation of training strategies for firefighters is not as straightforward; enhancing their capacity often equates to preparing for the unexpected, hence the need to develop a better appreciation for the transference of training. Certainly, general adaptations are possible and learning to perform various novel "exercises" could, theoretically, influence the execution of an unrelated or job relevant task, however the degree to which training transfers is probably individual-, task- and program-specific. Given that this area of study has received very little attention, there is much room to make substantial contributions by exploring the general and job-specific movement-related changes demonstrated in response to various interventions. Such work would add tremendous insight into the development of worker-centered physical preparation strategies for firefighters.

2.3. SUMMARY

Preventing injuries is not a trivial task, particularly within the fire service. Every individual will likely adopt a unique movement strategy to perform tasks of varying complexity and demand and exhibit dissimilar adaptations to any exercise intervention. However, it is this information that might be essential to the development of effective physical preparation strategies; an evaluation can be used to monitor changes and provide appropriate recommendations for training. Documenting *how* individuals perform will provide much better insight into injury risk than would any measure of muscular strength or endurance. An individual's movement patterns do reflect their fitness, but they also provide insight into their previous experiences, awareness and understanding – they offer an overall impression of capacity as it relates to the demands of the task being executed. By seeking to better understand the potential variation in movement patterns across several tasks and demands it is anticipated that scientists and practitioners will be able to develop superior injury screening methods and physical preparation strategies for various occupational groups. This thesis is separated into four studies, each of which examined a particular factor (i.e. number of trials, task demands, task specificity, and exercise intervention) that can influence the movement strategies adopted and the generalizability of any observations.

Chapter 3

INVESTIGATION ONE

MOVEMENT VARIABILITY AND THE ESTIMATION OF "MEANINGFUL"CHANGE

3.1. INTRODUCTION

Each of us is unique, both in the way we approach the execution of a particular task (Morriss et al., 1997, Rodano and Squadrone, 2002) and the manner in which we respond to various interventions (Caster and Bates, 1995, Dufek and Bates, 1990, Dufek et al., 1995). Our previous experiences, perceptions and expectations related to a given situation influence the movement strategies we adopt (consciously or subconsciously) to perform any activity (Dufek et al., 1995). But in the presence of between-subject variation (i.e. heterogeneity), averaging data across participants could lead to the conclusion of "no significant intervention effect" when substantial and clinically-relevant adaptations (positive and negative) are in fact exhibited by several of the study's participants (James and Bates, 1997). Or perhaps the effect is found to be significant, but the group's behaviour misrepresented the scope of individual strategies that were used (Caster and Bates, 1995, Dufek and Bates, 1990, Dufek et al., 1995, Scholes et al., 2012). This is precisely what was found by Dufek et al. (1995). The researchers examined how participants' adapted their maximum vertical ground reaction force while running in response to variations in stride length (normal, over-stride and under-stride) with group and single subject-analyses, and found that although 94.4% (17 of 18) of the subject-condition interactions were significant, none of the individuals performed using the group's mean strategy. Combining single-subject and group analyses may provide superior insight into participants' movement behaviour given that it would allow several movement strategies to be identified, facilitate the grouping of like responders and make it more feasible for researchers to evaluate the effectiveness of an intervention for a range of individuals who may not be represented by the aggregated data (James and Bates, 1997).

Understanding the degree to which a specific pattern or descriptor of motion varies across a population will undoubtedly assist with the development of effective worker-centered interventions; however, an effort must also be made to estimate the variability within participants. Movement patterns are inherently variable and thus each of us will never perform a given task in the exact same manner on multiple occasions (Hatze, 1986). According to Hopkins (2000), it is this type of variability that is most important for researchers because it impacts the precision of all experimental variables. Describing the movement patterns used to perform a particular task without acknowledging or accounting for the potential within-subject variation may drastically skew the conclusions and misdirect any recommendations being made. Best research practice may therefore be to identify the descriptors of motion that are least variable and thus better indicators of change. Conversely, if there are specific descriptors of motion that researchers wish to use as targets (e.g. knee abduction angle) to evaluate or train specific populations (e.g. firefighters), it may be prudent to first identify the magnitude of within-subject variation so that criteria can be developed to define boundaries, outside of which could be described as a biologically significant or "meaningful" change.

In general, collecting several trials of a given task is viewed as good scientific practice and thought to provide a more stable estimate of an individual's movement patterns (Bates et al., 1983), particularly if evaluating the effect of an intervention or contrasting multiple conditions. If too few trials are performed the observed variation may fall inside that which is typical for the dependent measures of interest (i.e. true dispersion), and therefore the actual study design could limit the interpretation of any findings. For this reason, the minimum number of trials necessary to achieve stable estimates of various descriptors of motion have been reported for a range activities, including running (Bates et al., 1983, DeVita and Bates, 1988), walking (Hamill and McNiven, 1990), vertical jumping (Rodano and Squadrone, 2002), lifting (Dunk et al., 2005), drop landing (James et al., 2007) and cricket bowling (Stuelcken and Sinclair, 2009). However, the number of trials needed has varied between four and twenty depending on the metric of interest and activity in question. Because it is often not practical or even possible to analyze twenty trials of a single condition, there is a need to explore alternative solutions that can be easily integrated into a number of methodological designs while accounting for the potential within- and between- subject variation.

Whether directed towards the prevention of injuries, improving performance or enhancing one's quality of life, knowledge pertaining to the potential variation in a population's movement strategies will undoubtedly increase the likelihood of the program's success. But, each individual's capacity is often evaluated within the context of their demands, and may therefore require the administration of multiple tasks; which for occupational groups such as firefighters might be chosen to reflect the general (e.g. heavy lifting) or specific (e.g. forced entry) demands they face while on the job. Given that tasks of dissimilar patterns/demands may elicit varying responses from each individual, it is also possible that the within-subject variation observed for each dependent measure will be task or demand-specific. Therefore, the objectives of this study were threefold: 1) to examine the between-session repeatability of select descriptors of motion, chosen to characterize the performance of four occupationally relevant tasks. The four tasks were chosen so that demand (i.e. heavy versus light) and task comparisons could be made; 2) to explore the within-subject variation of each of dependent measure, including its repeatability between-sessions; and 3) to evaluate the potential in using the within-subject variation as a criterion with which to define biologically significant or "meaningful" within-subject differences between multiple conditions or testing sessions. The within-subject variation may provide a means to establish a range for each subject, outside of which could be defined as a "meaningful" difference, whether participants perform 25, 10 or even 3 trials of a particular task, so that future work is not limited to group analyses or constrained by the heterogeneity of the participants.

3.2. RESEARCH DESIGN AND METHODS

3.2.1. Experimental Overview

A repeated measures study design was used to examine the between-session repeatability of select descriptors of motion that were used to characterize the performance of two sagittal plane lifts and two simulated firefighting tasks. The within-subject variation was also investigated for each variable, but treated as a separate dependent measure. Professional firefighters were recruited and randomly assigned to one of two groups (lifting or firefighter), each requiring participants to attend three testing sessions. The first two sessions were performed on the same day, separated by fifteen minutes of passive recovery. The final session was completed on a second day within one week of the first collection. Participants assigned to the lifting and firefighter groups performed only lifting and firefighting tasks, respectively. During each collection, participants were instrumented with infrared markers and asked to perform twenty-five repetitions of each task (five sets of five). The ten total sets (two tasks) performed in each session were completed in a randomized fashion. The magnitude and within-subject variation of every motion-related variable were described for each session using means and standard deviations. Sequential averaging was used to explore the efficacy of using the within-subject variability to define biologically significant or "meaningful" within-subject differences.

3.2.2. Participant Selection

Twenty professional firefighters (18 men and 2 women) from the Waterloo and Kitchener Fire Departments were recruited to participate in this investigation. Ten (9 men and 1 woman) were randomly assigned to each of the two groups (lifting and firefighter). A description of the participants can be found in Table 3.1. Exclusion criteria included musculoskeletal injury or pain at the time of testing and firefighters that were on assigned light duty. The study was approved by the Human Research Ethics Committee of the University and all participants gave informed consent confirming their involvement, prior to beginning the study.

Table 3.1. The mean (standard deviation) age, height and body mass of participants in either group.

GROUP	Age (years)	Height (m)	Body mass (kg)
Lifting	35.1 (7.8)	1.79 (0.03)	88.0 (13.3)
Firefighter	32.3 (6.4)	1.81 (0.07)	89.6 (16.0)

3.2.3. Task Selection

The tasks were chosen to replicate two general and two occupation-specific patterns of varying demands (Figure 3.1). The four tasks were: 1-2) Box lift (two different masses) - from standing, individuals were instructed to lift a box (0.33 x 0.33 x 0.28 m) to waist height and return it to the ground at a self-selected pace; 3) Hose drag – a 6.4 cm diameter rope, connected to a cable machine was placed over the right shoulder and held across the body. Individuals were instructed to initiate movement from a staggered stance with their left foot forwards; and 4) Forced entry – individuals struck a ceiling-mounted "heavy bag" with a 4.5 kg sledgehammer (direction of swing was self-selected).

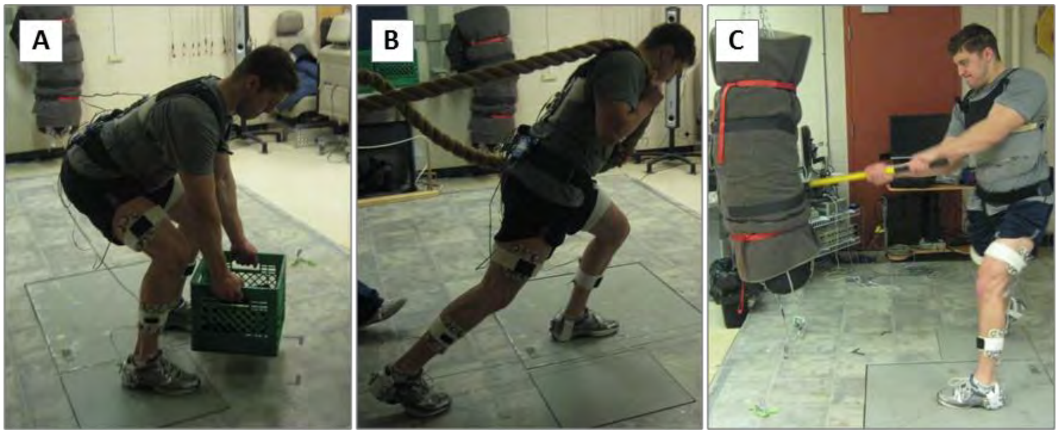


Figure 3.1. The A) Box lift; B) Hose drag; and C) Forced entry tasks.

3.2.4. Experimental Protocol

Upon arriving for the first session, participants were instrumented with infrared markers for kinematic tracking and familiarized with the tasks they would be asked to perform using a standard set of instructions. Individuals assigned to the lifting condition performed two variations of the box lift: 1) light load (6.8 kg) at a controlled cadence, and 2) heavy load (22.7 kg – NIOSH recommended maximum (Waters et al., 1993)) at a controlled cadence. Participants in the firefighter group performed a simulated hose drag and forced entry task. The hose drag was resisted by a cable load of approximately 13 kg (load attached in series with rope). Twenty-five repetitions (five sets of five) of each movement were completed. Each set of five repetitions for the two tasks was completed in random order (e.g. two sets of heavy box lifts followed by one set of light box lifts, etc.). Approximately 15 seconds and 2 minutes of rest were given between trials and tasks, respectively. Once five sets of each task had been completed, participants were given 15 minutes to recover prior to beginning the second test session, during which time they were asked to sit or stand. The order of testing for the second session was identical to that used during the first. Participants were asked to return for a third session, identical to that of the first two, within one week of day one. No feedback was given regarding task performance at any point throughout the investigation. A t-shirt, shorts and athletic shoes were worn at all times.

3.2.5. Data Collection and Signal Processing

Three-dimensional motion data was measured using an active motion capture system (Optotrak® Certus™, NDI, Waterloo, ON, Canada). The medial/lateral proximal and distal endpoints of the trunk, pelvis, thighs, shanks and feet were located with a digitizing probe, although the hip joint centers (HJC) and knee joint axes (KJA) were also determined "functionally" using similar methods to those described by Begon et al. (2007) and Schwartz and Rozumalski (2005). Briefly, participants were asked to perform 10 repetitions of open-chain hip flexion/extension, abduction/adduction and circumduction (all with the knee extended) and open-chain knee flexion/extension for the hip and knee joint computations, respectively. Visual 3D™ software (Version 4, C-Motion, Inc., Germantown, MD, U.S.A.) was used to calculate the axis of rotation between every pair of measured adjacent segment configurations. The most likely intersection and orientation of the axes were used to define the effective joint centers and joint axes, respectively. Using functionally defined segment endpoints for the shank and thigh has been shown to minimize the variation introduced via digitization and thus provide a more stable way to create each individual's link segment model (Frost et al., 2012c), which is extremely important when making between-day comparisons. Sets of 5 or 6 markers, fixed to rigid pieces of plastic, were secured to each segment with Velcro® straps and used to track the position and orientation of each body segment in 3D space throughout the collection. However, each thigh segment was tracked with the pelvis and corresponding shank to minimize the influence of soft tissue motion artifact (Frost et al., 2012b). One static calibration trial (standing) was collected such that the orientation of each segment's local axis system, as defined by its endpoints, could be determined via a transformation from an axis system embedded within each rigid body. The marker data was collected at 32 Hz, padded with one second of data (Howarth and Callaghan, 2009) using an end-point reflection method (Smith, 1989) and smoothed with a low-pass filter (4th order, dual pass Butterworth) with a cut-off frequency of 6 Hz (Winter, 2005).

3.2.6. Data Analyses

To characterize the movement patterns used to perform each of the four tasks, nine variables of interest were computed with Visual 3D™ software. Each was chosen to either reflect a possible mechanism for injury (e.g. spine motion (Callaghan and McGill, 2001, Lindsay and Horton, 2002, Marshall and McGill, 2010) and frontal plane knee motion (Chaudhari and Andriacchi, 2006, Hewett et al., 2005, Hewett et al., 2009)) or a coaching observation that is commonly used to differentiate individuals' performance (e.g. trunk angle relative to the vertical). Although these observations have not been cited as mechanisms for injury, each has been listed previously as a possible risk factor (Marras et al., 1993, Punnett et al., 1991) or shown to influence the knee, hip or low back moments while squatting (Fry et al., 2003, King et al., 2009) or lifting (Straker, 2003). The nine variables were: 1-3) spine flexion/extension (FLX), lateral bend (BND) and axial twist (TST) – the relative orientation of the trunk was expressed with respect to the pelvis (Woltring, 1991) and the corresponding direction cosine matrix was decomposed with a rotation sequence of flexion/extension, abduction/adduction and axial rotation (Cole et al., 1993) to compute the spine angle about each axis. The orientation of the lumbar spine in a relaxed upright standing trial was defined as zero degrees; 4) trunk angle relative to the vertical (TRK) – the relative orientation of the trunk (flexion/extension only) was expressed with respect to an "imaginary" pelvis segment that was free to move with the body, but constrained about the flexion/extension axis, thus remaining upright; 5) shank angle relative to the vertical (SHK) – the relative orientation of the left and right shank (flexion/extension only) was expressed with respect to the “imaginary” pelvis segment; 6) hip to ankle distance (HIP) – using the “imaginary” pelvis described above to define a body-fixed anterior/posterior (A/P) axis, the position of each hip joint in the A/P direction was described relative to the same side ankle (mid-point of medial and lateral anatomical landmarks); 7) knee to ankle distance (KNE) – the A/P position of each knee joint in the A/P direction was described relative to the same side ankle; and 8-9) left (LFT) and right knee (RGT) position relative to the frontal plane – the position of each knee joint in the medial/lateral direction was described relative to a body-fixed plane created using the corresponding hip joint, ankle joint and distal foot (mid-point of medial and lateral anatomical landmarks). The SHK, HIP and KNE variables were only computed for the lead leg (left) of the firefighting tasks and defined as an average of the left and right sides for lifting. Figure 3.2 provides a visual representation of each variable as it relates to the lifting, hose drag and forced entry tasks.

To objectively define the start, mid-point (lifting only) and end of each trial, event detection algorithms were created in Visual 3D™ by tracking the motion of the trunk, pelvis and whole-body center of mass. The lifting tasks were separated into a descent and ascent phase to capture any movement pattern changes that were exhibited once the load had been placed in the hands. Two firefighters chose to perform the forced entry task from the left side, but their data was processed to reflect a right handed swing (as was seen for the rest of the group). To verify that events were defined as intended, model animations of all trials were inspected visually. Maximums, minimums, ranges and means were computed for the nine dependent variables (each phase separately) and the data series were normalized to twenty samples so that time-series comparisons could be made across trials, sessions and participants. The “peak” of each variable, with the exception of BND and TST, was described as the deviation (maximum or minimum) hypothesized to be most relevant to the characterization of each pattern (i.e. FLX – flexion, TRK and SHK – forward bend, HIP – posterior displacement, KNE – anterior displacement, LFT and RGT – medial displacement). Peak BND and TST were described as the range (i.e. max – min) observed for the specified phase. The within-subject variation is presented as an aggregate score of the 25-trial within-session standard deviations that were computed for each subject (i.e. group average).

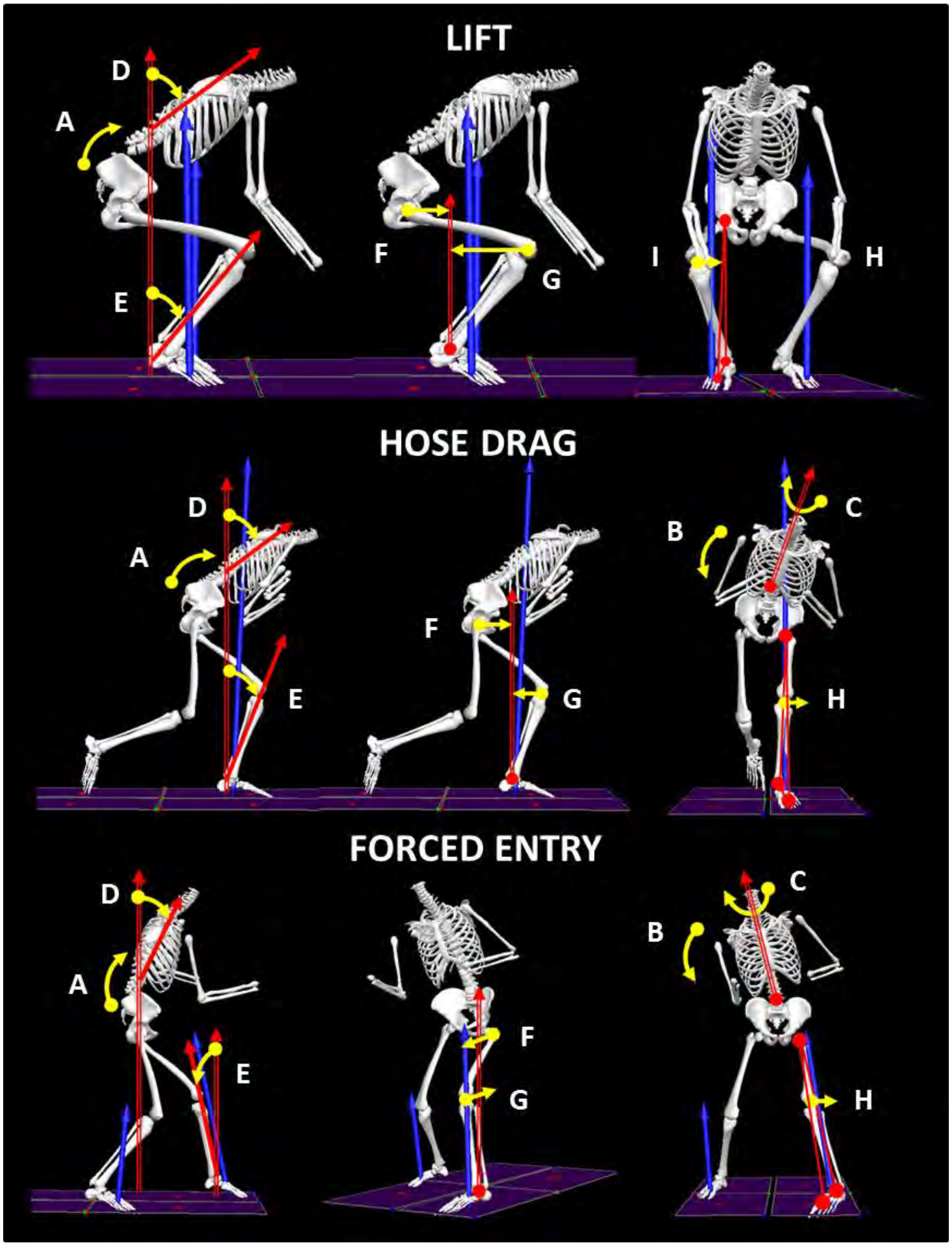


Figure 3.2. Participants` movement patterns were characterized with the following variables: A) spine flexion/extension (flexion → +); B) spine lateral bend (bend right → +); C) spine axial twist (twist right → +); D) trunk angle (forward → +); E) shank angle (forward → +); F) hip-ankle distance (anterior → +); G) knee-ankle distance (anterior → +); H) left knee position (lateral → +); I) right knee position (medial → +).

3.2.7. Statistical Analyses

The 25-trial means for each of the four tasks were used to examine the between-session repeatability of each dependent measure. The magnitude and within-subject variation (group average) of the maximums, minimums and means for each task were investigated separately. Comparisons were made using a general linear model with one within-subject factor (i.e. session) (IBM SPSS Statistics, Version 20.0, Armonk, NY, U.S.A.). Significant session effects were described by p-values less than 0.05. To assess the differences amongst the participants and thus the potential limitations of a group design, a second group of analyses were conducted whereby the subjects were treated as an independent factor (blocked design). Once again, comparisons were made with a general linear model but subject was included as a "between-subject" factor. Because the error term for the within-subject factor was equivalent to the subject × session interaction, only significant ($p<0.05$) main effects are presented.

In light of the findings from the analyses described above, demand (i.e. heavy versus light lifts) and task (i.e. hose drag versus forced entry) comparisons were made (separately) on the within-subject variation for each dependent variable. The influence of each factor (demand or task) was examined with a general linear model with one repeated measure (the data were collapsed across all three sessions), and significant differences were described by p-values level less than 0.05.

"Meaningful" Within-Subject Differences

The 25-trial mean (group average) and the between- and within-subject variation were plotted against the sequential mean (average of 2, 3, 4, etc. trials) for each metric (i.e. maximum, minimum and mean) of every variable computed (Figure 3.3). Based on previous work (Bates et al., 1983, DeVita and Bates, 1988, Dunk et al., 2005, Hamill and McNiven, 1990, James et al., 2007, Rodano and Squadrone, 2002, Stuelcken and Sinclair, 2009), it was hypothesized that 25 trials would be sufficient to establish a stable estimate of the mean, and thus an approximation of the expected dispersion for a particular variable (i.e. how much variation could be expected if participants were given an opportunity to perform an unlimited number of trials). The variability observed across 2, 3, 4, etc. trials was expected to fall primarily within a range bounded by the 25-trial mean ± the within-subject variation (red lines in Figure 3.3), which would imply that 25 trials were able to provide a reasonable estimate of the variation displayed. However, given that the proposed method was intended to help describe within-subject differences whether three, five or fifteen trials were collected, the boundary criteria could not be established using a 25-trial average; instead they had to be defined using the number of trials available. Furthermore, if the boundaries were in fact going to provide a reasonable estimate of a "meaningful" difference, it was considered important for the 25-trial variation to lie within this range (i.e. a "meaningful" difference was larger in magnitude than the variation observed across 25 trials). To accomplish this objective, boundary criteria were established whereby the magnitude of a "meaningful" difference was described by the sequential within-subject variation + 1SD (SEQVAR). Because the within-subject variation describes a group average, raising the boundaries by 1SD was considered necessary so that the possible dispersion represented a greater percentage of the population being tested. This variation is illustrated by the shaded areas in Figure 3.3.

For all computed metrics of each dependent variable, the sequential mean was subtracted from the 25-trial variation (mean ± within-subject variation) and expressed as a function of the SEQVAR (i.e. metric used to define "meaningful" within-subject changes). Both the upper and lower boundaries were investigated, but the differences were expressed as a magnitude only. A value less than or equal to 1.0 implied that the 25-trial / sequential mean difference was contained by the boundary criteria. The utility of this method was evaluated for each task by computing the number of instances (high and low) across all variables whereby the computed difference was less than or equal to 1.0 (i.e. red dashed line was contained by the shaded area in Figure 3.3). For each task, the number of successful instances (25-trial variation captured) was expressed as percentage of the total number possible. To investigate the impact that the number of collected trials might have on the utility of this method, the analyses were conducted using all trial averages between 2 and 25. Each session was evaluated separately.

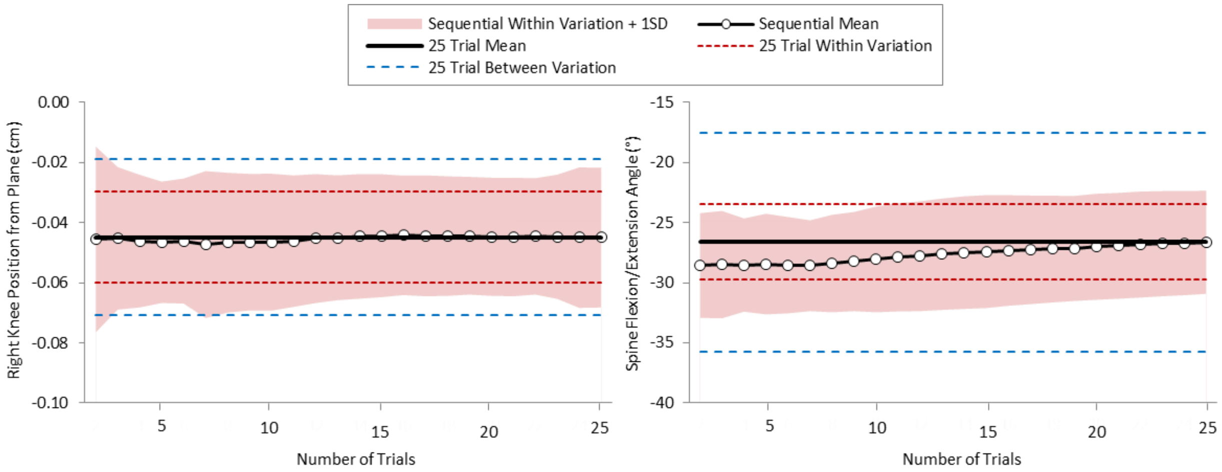


Figure 3.3. The sequential mean, 25-trial mean, 25-trial between-subject variation and the 25-trial within-subject variation for two sample variables. The shaded area reflects the sequential mean ± the sequential within-subject variation + 1SD. This method was used to evaluate the number of instances wherein the 25-trial mean ± the within-subject variation (-----) was captured by the boundary conditions created by the shaded area. If the line was contained by the shaded area, the observed score was within the "true" dispersion as estimated by the 25 trial mean. The boundaries defined using this approach may assist in establishing "meaningful" within-subject differences when contrasting conditions or evaluating the effect of an intervention, particularly if a limited number of trials were collected.

3.3. RESULTS

3.3.1. Lifting Tasks

For both the heavy and light conditions, session was only found to be a significant factor ($p<0.05$) for TRK and HIP (Table 3.2 and Table 3.3), and with the exception of peak HIP during the heavy lift, differences were limited to the mean of the descent phase (Table 3.2). Subject, however, was a significant factor for each variable investigated.

In regards to the within-subject variation, session was also found to be a significant factor ($p<0.05$) for select variables (Figure 3.4). The peak and mean SHK and KNE variation of the descent phase (heavy lift) and all instances for TRK (light lift) were influenced by session ($p<0.05$). As above, subject was a significant factor for each variable investigated. Substantial differences were also found in the within-subject/between-subject variation ratio across variables. For example, the within-subject FLX and HIP variation were approximately 19-33% and 47-73%, respectively, of that seen between-subjects (Figure 3.4).

Table 3.2. The 25-trial mean (standard deviation) of sessions 1, 2 and 3 (S1-S3) for the HEAVY lifting task. The peak and mean of the descent phase (unloaded) and the mean of the ascent phase (load in hands) are described. P-values for *Session* and *Subject* are also included.

HEAVY		Spine Flex/Ext (°)	Trunk Angle (°)	Shank Angle (°)	Hip - Ankle Distance (cm)	Knee - Ankle Distance (cm)	Left Knee Position (cm)	Right Knee Position (cm)
PEAK Descent (Unloaded)	S1	39.7 (10.7)	53.7 (16.5)	30.7 (9.7)	-19.3 (2.2)	19.4 (5.4)	-1.1 (2.3)	4.5 (2.4)
	S2	38.9 (11.2)	52.6 (16.5)	30.8 (9.6)	-18.4 (2.4)	19.4 (5.6)	-0.5 (1.9)	4.3 (1.6)
	S3	39.7 (10.1)	56.1 (16.4)	29.3 (8.3)	-20.1 (2.7)	18.6 (4.8)	-1.4 (2.8)	5.1 (2.3)
	Session	*0.882*	*0.149*	*0.223*	***0.027***	*0.243*	*0.251*	*0.431*
	Subject	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***
MEAN Descent (Unloaded)	S1	29.9 (8.3)	43.3 (9.1)	16.7 (5.7)	-15.9 (2.4)	10.1 (3.4)	1.9 (2.7)	1.7 (3.0)
	S2	28.2 (9.7)	41.7 (7.6)	16.7 (5.6)	-15.1 (2.2)	10.6 (3.4)	2.5 (2.3)	1.8 (2.2)
	S3	30.5 (9.2)	45.9 (10.3)	15.3 (5.4)	-16.9 (2.8)	9.8 (3.2)	2.0 (3.8)	2.4 (2.7)
	Session	*0.514*	***0.036***	*0.215*	***0.026***	*0.176*	*0.519*	*0.550*
	Subject	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***
MEAN Ascent (Loaded)	S1	27.3 (8.6)	41.5 (11.6)	18.7 (6.9)	-13.1 (2.2)	12.0 (4.4)	2.7 (2.5)	0.6 (3.3)
	S2	27.4 (9.2)	41.4 (11.6)	19.3 (6.4)	-13.3 (2.4)	12.3 (4.1)	3.4 (2.4)	1.0 (2.7)
	S3	27.0 (9.7)	43.9 (12.7)	17.7 (7.5)	-13.2 (2.4)	11.3 (4.6)	2.9 (4.2)	1.3 (2.9)
	Session	*0.937*	*0.198*	*0.226*	*0.728*	*0.212*	*0.613*	*0.563*
	Subject	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***

Table 3.3. The 25-trial mean (standard deviation) of sessions 1, 2 and 3 (S1-S3) for the LIGHT lifting task. The peak and mean of the descent phase (unloaded) and the mean of the ascent phase (load in hands) are described. P-values for *Session* and *Subject* are also included.

LIGHT		Spine Flex/Ext (°)	Trunk Angle (°)	Shank Angle (°)	Hip - Ankle Distance (cm)	Knee - Ankle Distance (cm)	Left Knee Position (cm)	Right Knee Position (cm)
PEAK Descent (Unloaded)	S1	40.3 (11.1)	54.1 (16.9)	30.6 (9.1)	-19.3 (2.2)	19.4 (5.1)	-1.4 (2.0)	4.5 (2.6)
	S2	38.8 (11.1)	53.1 (16.5)	30.2 (10.1)	-18.7 (2.8)	19.1 (5.9)	-0.5 (1.8)	4.1 (1.6)
	S3	40.0 (10.1)	55.9 (15.2)	29.3 (8.1)	-20.2 (2.9)	18.6 (4.6)	-1.4 (2.7)	5.0 (2.3)
	Session	*0.731*	*0.324*	*0.378*	*0.086*	*0.369*	*0.208*	*0.381*
	Subject	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***
MEAN Descent (Unloaded)	S1	29.5 (8.1)	43.0 (9.4)	15.7 (5.2)	-16.0 (2.3)	10.1 (3.1)	1.4 (2.5)	1.8 (3.1)
	S2	27.8 (9.8)	41.9 (8.0)	15.9 (5.6)	-15.5 (2.3)	10.2 (3.4)	2.0 (2.3)	1.7 (2.0)
	S3	30.8 (9.4)	46.2 (10.2)	14.9 (5.2)	-17.2 (2.8)	9.5 (3.0)	1.7 (3.6)	2.3 (2.7)
	Session	*0.379*	***0.022***	*0.429*	***0.042***	*0.360*	*0.539*	*0.599*
	Subject	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***
MEAN Ascent (Loaded)	S1	26.6 (9.1)	40.8 (11.2)	21.2 (7.9)	-11.5 (2.7)	13.6 (4.9)	2.8 (2.7)	0.5 (4.1)
	S2	26.0 (9.5)	40.4 (11.3)	21.0 (7.4)	-11.8 (3.5)	13.4 (4.5)	3.2 (2.4)	0.7 (2.4)
	S3	25.9 (9.6)	42.0 (10.9)	20.3 (7.8)	-11.7 (2.6)	13.0 (4.6)	2.8 (3.9)	1.1 (3.3)
	Session	*0.815*	*0.320*	*0.580*	*0.690*	*0.528*	*0.701*	*0.632*
	Subject	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***

With the exception of three (of 21) instances, increasing the demands (i.e. load) of the lifting task had minimal impact on the within-subject variation (Figure 3.4). Significant differences ($p<0.05$) were found in the peak FLX, peak KNE and mean TRK variation of the descent phase, and interestingly in each instance the light lift was more variable.

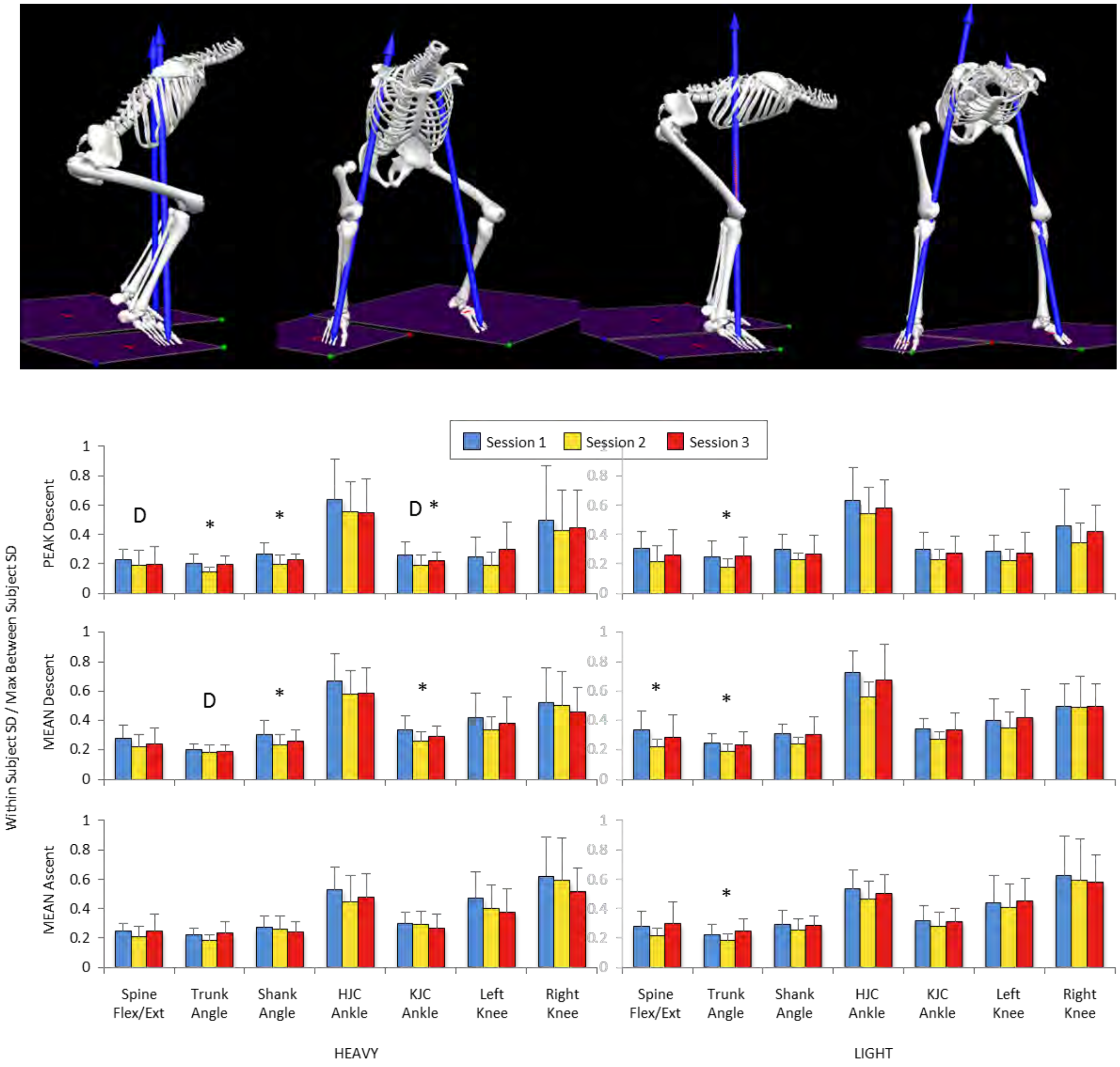


Figure 3.4. The 25-trial mean (standard deviation) within-subject variation exhibited during sessions 1, 2 and 3 for the HEAVY and LIGHT lifting tasks. Variation in the peak and mean of the descent phase (unloaded) and the mean of the ascent phase (load in hands) are presented as a function of the maximum between-subject standard deviation observed for a given variable (i.e. that of the peak, mean descent or mean ascent). Significant session effects ($p<0.05$) are described with an *. Instances marked with a D denote a significant difference ($p<0.05$) in the *within-subject variation* observed between the HEAVY and LIGHT conditions (i.e. a demand effect). Although not shown, *Subject* was also a significant factor across all variables for both conditions. The model skeletons shown above depict two unique movement strategies that were used to perform the lifting tasks.

3.3.2. Firefighting Tasks

As was found with lifting, session had little influence on the variables used to characterize the simulated firefighting tasks (Table 3.4 and Table 3.5). Between-session differences ($p<0.05$) were not evident amongst any of the metrics used to characterize the forced entry (Table 3.5), and noted in just seven of the twenty-four possible instances for the hose drag (Table 3.4). Once again, unique movement strategies were observed amongst participants (Figure 3.5) as subject was found to be a significant factor for each variable investigated.

With regards to the within-subject variation, only six hose drag- (max TRK, KNE, LFT and mean FLX, TST, TRK) and two forced entry-related (min BND and mean HIP) variables were influenced ($p<0.05$) by session (Figure 3.5). Interestingly however, the largest variation observed in each instance was seen during session one. Subject was found to be a significant factor across all variables.

Table 3.4. The 25-trial mean (standard deviation) of sessions 1, 2 and 3 (S1-S3) for the simulated HOSE DRAG task. The max, min and mean of the first step are described. P-values for *Session* and *Subject* are also included.

HOSE DRAG		Spine Flex/Ext (°)	Spine Bend (°)	Spine Twist (°)	Trunk Angle (°)	Shank Angle (°)	Hip - Ankle Distance (cm)	Knee - Ankle Distance (cm)	Left Knee Position (cm)
MAX	S1	36.0 (7.8)	8.0 (3.6)	13.2 (4.5)	66.5 (6.1)	58.2 (4.7)	57.8 (4.7)	33.9 (3.3)	6.1 (6.3)
	S2	39.1 (8.1)	9.3 (4.0)	14.5 (4.9)	67.8 (7.1)	59.9 (4.5)	59.4 (5.5)	34.6 (3.2)	6.5 (5.4)
	S3	40.0 (8.5)	10.1 (3.2)	12.3 (3.4)	69.4 (5.5)	60.7 (3.5)	60.3 (5.2)	35.2 (2.8)	6.6 (5.4)
	Session	*0.110*	*0.153*	***0.048***	*0.250*	*0.061*	***0.009***	***0.020***	*0.799*
	Subject	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***
MIN	S1	16.9 (5.4)	-13.5 (3.8)	-4.3 (3.4)	35.4 (6.7)	10.7 (5.2)	-17.6 (4.8)	7.1 (3.6)	-3.6 (3.9)
	S2	21.0 (5.7)	-12.6 (4.4)	-2.8 (4.2)	38.6 (8.5)	12.6 (7.6)	-15.8 (5.3)	8.5 (5.4)	-3.1 (3.5)
	S3	21.1 (6.6)	-12.9 (3.5)	-4.2 (3.6)	41.5 (11.7)	13.0 (8.1)	-14.2 (6.3)	8.8 (6.1)	-2.7 (3.1)
	Session	***0.037***	*0.477*	*0.145*	*0.112*	*0.256*	*0.158*	*0.241*	*0.286*
	Subject	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***
MEAN	S1	26.3 (6.1)	-5.9 (2.6)	2.8 (2.5)	50.5 (6.6)	35.7 (5.4)	3.7 (3.4)	22.2 (3.5)	1.2 (4.9)
	S2	30.1 (6.5)	-5.2 (3.4)	4.3 (3.0)	53.1 (7.2)	37.2 (6.5)	4.5 (4.8)	22.9 (4.2)	1.4 (3.9)
	S3	30.7 (6.5)	-5.3 (2.1)	2.4 (2.4)	55.8 (7.1)	38.3 (5.3)	6.0 (5.7)	23.7 (3.9)	1.8 (4.1)
	Session	***0.042***	*0.511*	***0.009***	***0.031***	*0.076*	*0.203*	*0.063*	*0.653*
	Subject	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***

Table 3.5. The 25-trial mean (standard deviation) of sessions 1, 2 and 3 (S1-S3) for the simulated FORCED ENTRY task. The max, min and mean between the initiation of movement and contact are described. P-values for *Session* and *Subject* are also included.

FORCED ENTRY		Spine Flex/Ext (°)	Spine Bend (°)	Spine Twist (°)	Trunk Angle (°)	Shank Angle (°)	Hip - Ankle Distance (cm)	Knee - Ankle Distance (cm)	Left Knee Position (cm)
MAX	S1	29.7 (6.2)	11.6 (6.5)	13.5 (9.1)	36.0 (4.6)	35.7 (10.9)	12.5 (9.6)	22.3 (7.0)	8.5 (3.6)
	S2	31.9 (5.1)	10.7 (6.6)	15.6 (9.9)	36.3 (4.1)	39.2 (13.0)	14.3 (11.0)	24.0 (7.3)	8.4 (3.8)
	S3	31.4 (4.6)	10.6 (5.2)	14.4 (11.1)	37.0 (3.6)	42.3 (13.9)	17.8 (9.2)	25.5 (7.1)	8.3 (5.4)
	Session	*0.341*	*0.535*	*0.148*	*0.635*	*0.150*	*0.199*	*0.158*	*0.951*
	Subject	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***
MIN	S1	12.4 (4.4)	-3.6 (8.4)	-3.7 (10.3)	15.3 (3.9)	3.1 (6.1)	-23.1 (6.9)	1.9 (4.4)	-5.9 (5.2)
	S2	14.3 (3.8)	-3.9 (8.1)	-2.9 (9.8)	15.0 (3.1)	2.5 (6.9)	-23.8 (7.6)	1.6 (4.8)	-6.8 (5.2)
	S3	13.8 (4.4)	-3.9 (8.1)	-3.9 (9.9)	15.1 (2.7)	2.0 (5.9)	-24.9 (7.1)	1.4 (4.3)	-7.4 (6.4)
	Session	*0.289*	*0.859*	*0.635*	*0.964*	*0.488*	*0.248*	*0.642*	*0.127*
	Subject	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***
MEAN	S1	19.6 (3.7)	4.2 (3.3)	8.4 (4.4)	24.2 (2.8)	20.3 (7.0)	0.2 (5.8)	12.9 (5.1)	-1.8 (3.1)
	S2	21.5 (3.3)	3.6 (3.6)	8.8 (3.5)	24.2 (3.0)	20.8 (7.3)	0.2 (5.6)	13.1 (4.9)	-2.0 (3.1)
	S3	21.6 (3.3)	4.0 (3.3)	9.6 (3.3)	25.0 (2.0)	22.9 (7.7)	2.4 (3.2)	14.2 (5.0)	-2.3 (4.0)
	Session	*0.166*	*0.697*	*0.538*	*0.637*	*0.305*	*0.208*	*0.351*	*0.504*
	Subject	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***

Task was found to have a significant impact ($p<0.05$) on the within-subject variation observed for thirteen of the twenty-four variables used to characterize the hose drag and forced entry (Figure 3.5); max FLX, TRK, HIP and KNE, all minimums with the exception of HIP and KNE, and mean HIP, KNE and LFT. The hose drag was more variable in eight of these instances.

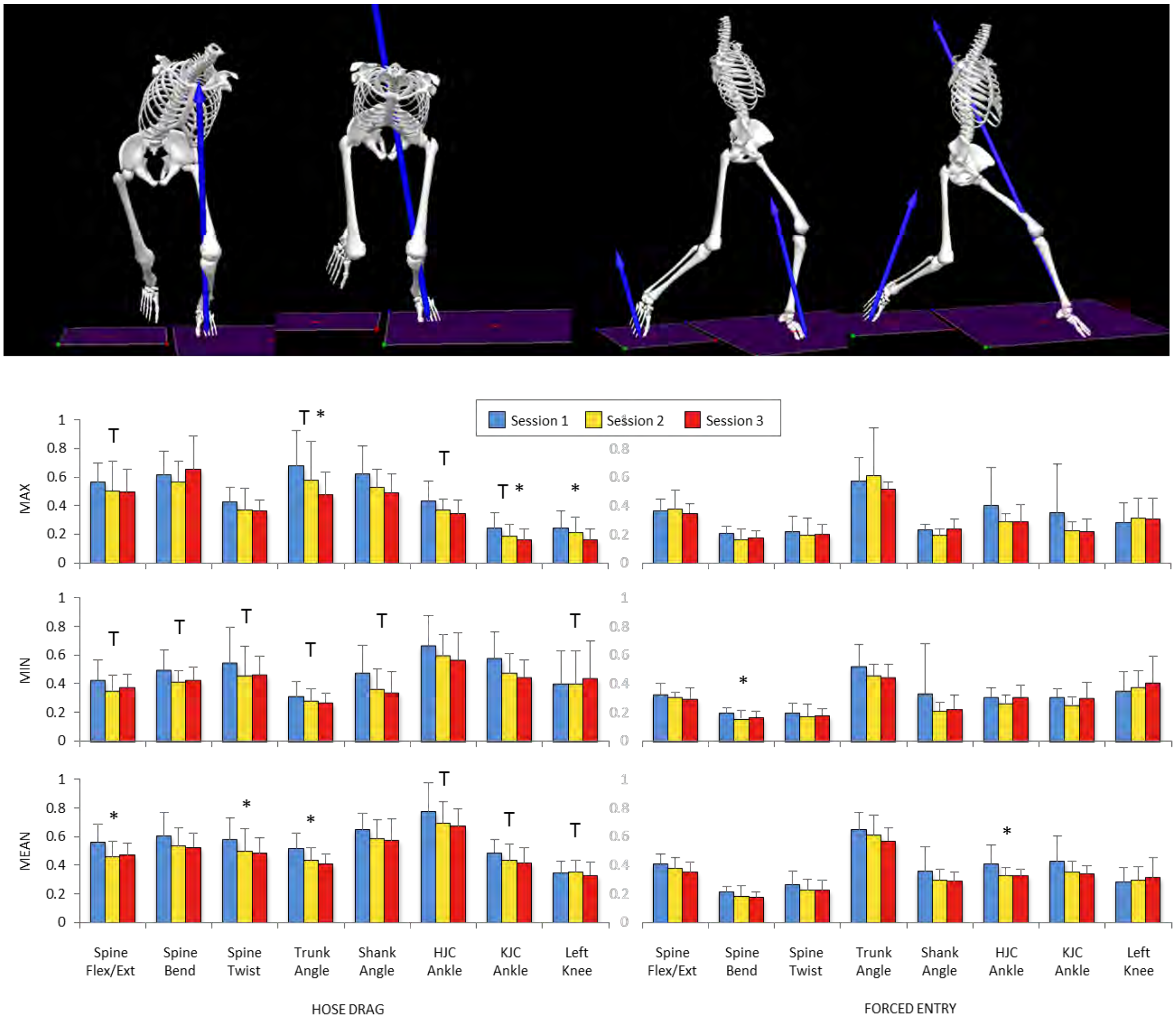


Figure 3.5. The 25-trial mean (standard deviation) within-subject variation exhibited during sessions 1, 2 and 3 for the simulated HOSE DRAG and FORCED ENTRY tasks. Variation in the max, min and mean of each task is presented as a function of the maximum between-subject standard deviation observed for a given variable (i.e. that of the max, min or mean). Significant session effects ($p<0.05$) are described with an *. Instances marked with a T denote a significant difference ($p<0.05$) in the *within-subject variation* observed between the two tasks (i.e. a task effect). Although not shown, *Subject* was also a significant factor across all variables for both tasks. The model skeletons shown above depict two unique movement strategies that were used to perform the simulated HOSE DRAG (left) and FORCED ENTRY (right).

3.3.3. “Meaningful” Within-Subject Differences

Because session was not found to be a significant factor in most cases, the session data was collapsed and is presented together. The number of instances wherein the 25-trial mean (± the within-subject variation) was contained within the boundaries established by the SEQVAR (i.e. metric proposed to define “meaningful” within-subject changes) increased as the aggregate scores comprised more trials (Figure 3.6). However, using a sequential average of only two trials was still able to capture approximately 70% of all 25-trial means; a trend that was evident for each of the four tasks investigated (Figure 3.7). In fact, the boundaries defined by the SEQVAR were able to capture approximately 74%, 81% and 89% of all 25-trial means using averages of three, five and ten trials, respectively (Figure 3.7). Twenty trials were needed to contain 100% of the 25-trial means within the boundary conditions.

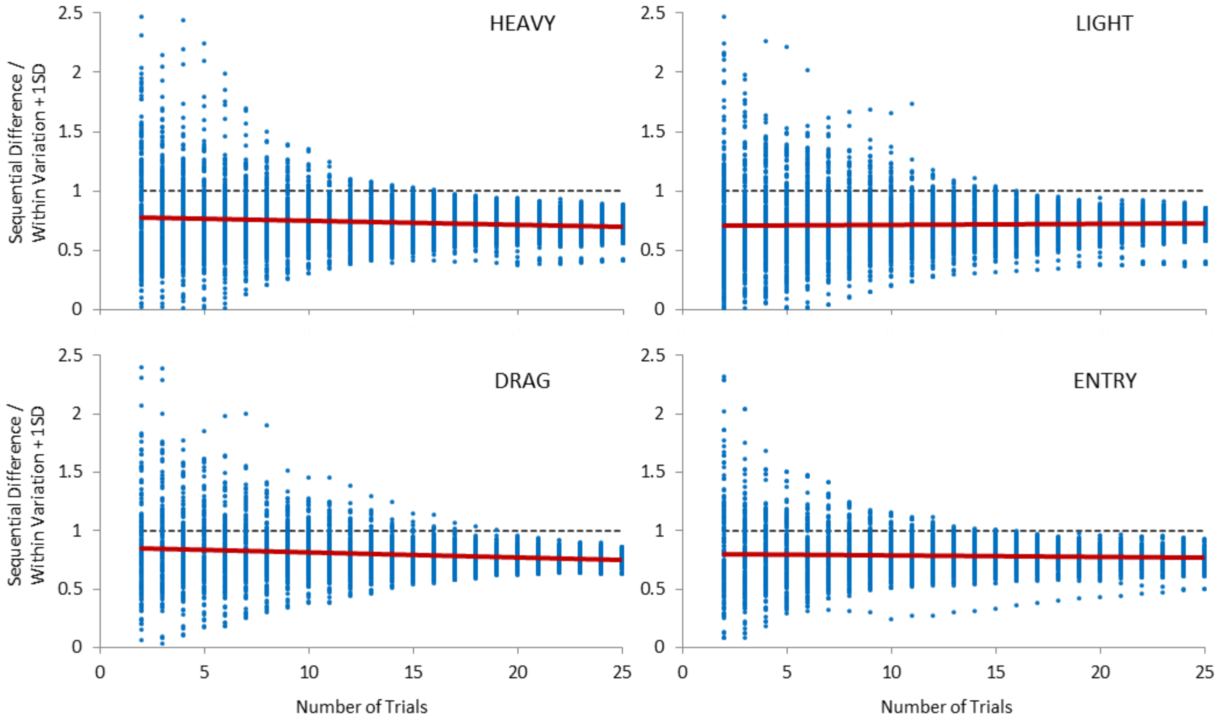


Figure 3.6. The 25-trial mean ± the within-subject variation minus the sequential mean was expressed as a function of the sequential within-subject variation + 1SD (i.e. metric proposed to define “meaningful” within-subject changes) for all computed metrics (e.g. mean) of each variable (e.g. spine flexion/extension) and session (1, 2 and 3). A value less than or equal to 1.0 implies that the 25-trial mean / sequential mean difference was captured within the boundaries defined by the sequential within-subject variation + 1SD. Each data point represents a unique metric and the solid red line (—) is a linear trendline across all data points. The four tasks are presented separately.

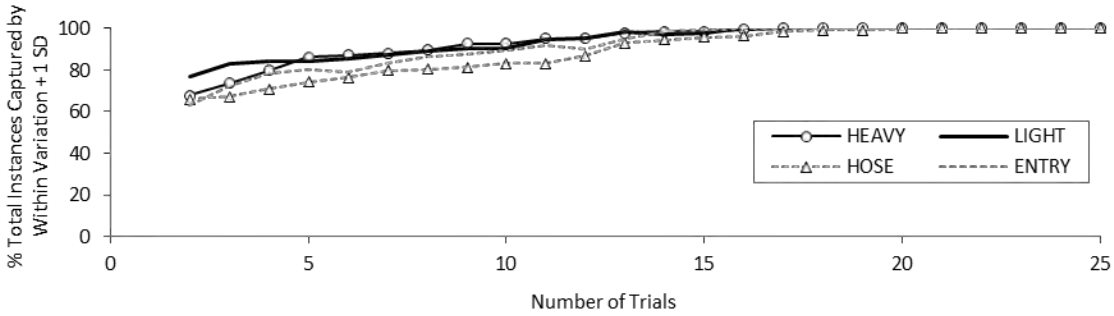


Figure 3.7. The number of instances across all metrics (i.e. maximum, minimum and mean), variables and sessions (expressed as a % of the total number possible) whereby the sequential within-subject variation (+ 1SD) was larger than the 25-trial mean - sequential mean difference.

3.4. DISCUSSION

Movement patterns are inherently variable. Each of us will never perform a specific task in the exact same manner on multiple occasions (Hatze, 1986), nor will we adopt a movement strategy identical to that of someone else. Although this intra- and inter-individual variability is often perceived as “noise” that affects the power to detect differences between multiple conditions (van Dieen et al., 2002), movement variability may be “functional” (Davids et al., 2003) and perhaps reveal important information regarding the task, environment or individuals being studied and should probably be considered to correctly interpret any findings (Mathiassen et al., 2003). Without knowledge pertaining to the variability of a given dependent measure the utility of any evaluation, including its ability to detect biologically significant changes in an individual’s performance, will be limited (Scholes et al., 2012). In this investigation, the variables chosen to describe the firefighters’ movement patterns were shown to be repeatable for each of the four tasks examined; however, in every instance, subject was also found to be a significant factor, implying that individuals exhibited movement strategies that were dissimilar from the group.

Group analyses are often used to highlight the mean response to a particular condition or intervention, but can be limited by the variability observed between and within participants (Scholes et al., 2012). For example, if a range of movement strategies were adopted to perform a given task (i.e. between-subject variability), as is typically the case, the group's response may not reflect that of any of the participants tested (Bates, 1996, Caster and Bates, 1995, Dufek et al., 1995). In many investigations this outcome may not be relevant; however, if the objective is to better understand one's risk of injury or devise an appropriate intervention to enhance the safety and effectiveness of an occupational group such as firefighters, each individual's response will be very important; it can provide insight into their abilities, awareness and understanding, and help to establish the most appropriate recommendations for training (coaching, fitness or otherwise). Alternatively, consider the situation wherein each individual's response does reflect that of the group (e.g. positive change), but the average change is not of a magnitude that can be described as significant because substantial between-subject variation was documented. In this case, it is possible that there were several "meaningful" within-subject changes masked by the group's variability. Had the within-subject variation been used to describe the observed changes (it is typically much smaller than that seen between subjects (Grills et al., 1994), the results may have shown that every participant exhibited a "meaningful" positive adaptation to the intervention tested. But because this was not the case, it is more likely that the findings of an investigation such as this one would be reported as inconclusive or not significant, thereby leading the authors and all subsequent readers to dismiss the utility of the intervention when in fact it was indeed effective.

The source, importance and role of movement variability has been a point of contention for years, which is why the inter- and intra-subject variation are frequently reported by authors seeking to better understand how a task, condition or intervention impacts participants' movement behaviour (e.g. Granata et al., 1999, Grills et al., 1994, Kjellberg et al., 1998, Mathiassen et al., 2003, Mirka and Baker, 1996, Scholes et al., 2012, van Dieen et al., 2002). Several metrics have been used to describe this dispersion, although the most widely adopted may be the coefficient of variation (CV) given that it provides a normalized estimate that can be contrasted against other variables and used to make comparisons with previous work. However, a CV may have little meaning if it is not computed on ratio scale data (i.e. non-negative), and thus its utility in helping to define biologically relevant within-subject changes will be limited. For instance, the CVs of the maximum and minimum knee to ankle distance during session one of the forced entry task were 31% and 232%, respectively, which would suggest that the maximum distance was far more repeatable. But this was not the case. The standard deviation (i.e. between-subject variation) of the maximum score was 1.6 times higher than that of the minimum. Because the variables were measured on an interval scale comprising negative and positive values (and an arbitrary zero) the CV was not an appropriate measurement to estimate the variation of each descriptor chosen to characterize participants' movement patterns. As an alternative, the variation of each dependent measure was described by dividing the within-subject variation by that seen between participants. This approach ensured that comparisons could still be made across variables and tasks and with future research, and provided an opportunity to highlight the potential differences in the variation observed between and within participants. Not surprisingly, there was more variability seen amongst the group than was exhibited by each firefighter for every variable and task investigated, lending further support to the fact that in many cases, our analyses and thus the interpretation of any findings might be constrained by the heterogeneity of the participants.

Various statistical analyses have been used to determine the minimum number of trials necessary to achieve a stable estimate of the mean for a range of variables and activities (Bates et al., 1983, DeVita and Bates, 1988, Dunk et al., 2005, Hamill and McNiven, 1990, James et al., 2007, Rodano and Squadrone, 2002, Stuelcken and Sinclair, 2009). It has also been shown that increasing the sample size or the number of trials collected for a particular condition can reduce the between-subject variation (van Dieen et al., 2002). This work has helped to highlight the potential limitations in collecting too few trials and brought attention to the impact of movement variability, but it has not necessarily offered a viable solution to deal with the inter- and intra-individual variation that will be seen across a range of methodological designs, nor has it provided a means to describe "meaningful" within-subject changes. Slight modifications to a task, condition or the pool of subjects being tested will likely alter the variation associated with a particular variable, and thus, require a different number of trials to achieve a stable estimate of the dispersion (at least according to the specified criteria). Further, and perhaps more importantly, collecting a large number of trials is often not feasible or conducive to investigating the experimental hypotheses. If evaluating the effect of an intervention or contrasting multiple conditions, collecting several trials would likely provide a better representation of an individual's movement patterns, but for a variety of reasons it may simply not be an option.

Participants were found to exhibit considerable variation across trials, thereby reinforcing the fact that movement is inherently variable, but interestingly, the magnitude of this dispersion was shown to be repeatable across sessions, unaffected by load (while lifting) and unique to the task investigated. For these reasons, it was hypothesized that the within-subject variation may in fact provide a means to establish a range for each dependent measure, outside of which could be defined as a "meaningful" difference. The method detailed in this paper was comparable to previous work that has sought to describe clinical differences (e.g. Knutson, 2005) or make meaningful inferences regarding subjects' performance using confidence limits (e.g. Batterham and Hopkins, 2006), but instead used the participants' within-subject variation to define boundary criteria so that each individual's movement patterns could be examined. The aim was to provide researchers with a simple means to evaluate the way that each of their participants adapt in response to a given task, condition or intervention without having to collect a large number of trials.

As expected, the utility of the proposed method, defined by the number of instances whereby the 25-trial variation was captured by the participants' variability, did improve as more trials were used to compute the mean and within-subject variation of each dependent measure. However, using an average of only two repetitions was still able to capture the 25-trial variation in approximately 70% of all instances, irrespective of the task investigated (using three, five and ten trials increased the success rate to 74%, 81% and 89%, respectively). Although encouraging, these results do not imply that the method is capable of describing actual differences with this level of success in any investigation given that a unique set of variables and tasks were used to evaluate its effectiveness. Rather, this study investigated four complex, whole-body movements using dependent measures that were chosen *a-priori* without any knowledge pertaining to their potential variation. Had a different set of tasks or variables been used it is possible that this method could be even more effective. Furthermore, considering that many of the potential applications comprise task, condition, or pre-post comparisons, the measurements being evaluated will be represented by the mean of multiple trials, thereby removing the likelihood of comparing an outlier.

The mean *and* standard deviation of the group's within-subject variation were used to define the boundary criteria because of the relationship that was noted between the two variables. In general, as more trials were collected the mean and standard deviation were found to increase and decrease, respectively. Therefore, by using both variables, "meaningful" differences would be described by a similar magnitude irrespective of the number of trials being used to represent the participants' movement patterns. Collecting more repetitions of any condition will likely provide a more stable estimate of an individual's movement behaviour and thus improve the chances of identifying an actual difference, but it is not the only means of improving the method's success. As an alternative, the effectiveness can also be improved by adopting a more conservative estimate of the within-subject variation (i.e. larger), which would effectively extend the range being used to define the change limits. Whether accomplished by using the largest variation observed across all conditions and metrics for a particular variable (e.g. heavy or light maximum, minimum and mean), or raising the within-subject standard deviation (SD) to 1.5 or 2 ("meaningful" differences were defined herein by the within-subject variation + 1SD), both strategies will increase the odds of capturing a true meaningful difference.

Several factors including our perception of risk, awareness and whole-body coordination will influence how we perform a given task, and therefore, there is always a chance that an individual's true movement behaviour could be misrepresented by the findings of an investigation. It is for this reason that tremendous efforts are made to ensure that the experimental protocols, instrumentation and analytical tools used are in fact appropriate to explore the stated hypotheses. Unfortunately however, in many cases it is the group's variability and not the aforementioned factors that limit our interpretation of any findings. As a result, it is possible that we have impeded our own progress and dismissed several opportunities to better understand the prevention of musculoskeletal injuries or improvement of performance simply because we have not considered the individual. Each of us will adapt our movement patterns if asked to perform multiple trials of the same task, thus introducing a certain degree of within-subject variation, but the magnitude of this dispersion appears to be repeatable and much smaller than that observed amongst a group under the conditions examined. If an individual exhibits a movement pattern that is "different" by a magnitude beyond what could be considered as typical variation, it should arguably be described as "meaningful". Although much more evidence is needed to substantiate its use, the method proposed in this study may offer an effective means to explore an individual's movement behaviour by exploiting their within-subject variation.

3.5. CONCLUSIONS

The dependent measures chosen to characterize participants' movement patterns were found to be repeatable, although there was considerable variation seen between and within participants. Often and perhaps erroneously perceived as "noise", this intra- and inter-individual variability can skew the interpretation of any findings if it is not considered or accommodated by the experiment's analyses. Additional trials can be collected to provide a more stable estimate of the mean and a true measure of the dispersion, but such an option is not always possible and thus cannot be viewed as a viable solution that can be integrated into a variety of experimental designs. As a result, many studies are limited to group analyses and constrained by the heterogeneity of the participants because there has not been an effective means to examine the movement behaviour of each individual.

It would be naïve to hypothesize that every individual will perform a given task with the same movement strategy or exhibit identical adaptations to fluctuating environmental, task, or individual movement constraints. Because an individual's movement patterns are influenced by factors such as their previous experiences, perception of risk, awareness and whole-body coordination there is no single response that should be expected across an entire population. Proposed in this study was a novel method that could provide an opportunity to explore an individual's movement behaviour by exploiting their within-subject variation. Using select criteria to establish boundaries outside of which was described as a "meaningful" change, collecting just two trials resulted in a success rate of 70% (using three, five and ten trials increased the success rate to 74%, 81% and 89%, respectively). Although much more evidence is needed to substantiate its use, this method does offer a simple means to accommodate the between- and within-subject variation inherent to any investigation without having to collect a large number of trials, and therefore, could provide a tremendous opportunity to further explore various interventions designed to prevent musculoskeletal injury or improve performance.

Chapter 4

INVESTIGATION TWO

LOAD, SPEED AND THE EVALUATION OF MOVEMENT: A TASK'S DEMANDS INFLUENCE THE WAY WE MOVE

4.1. INTRODUCTION

The development of physical preparation strategies for "occupational athletes" such as firefighters, soldiers and police officers may require that emphasis be placed on better understanding the movement patterns used to perform the tasks most relevant to their demands. Evaluating an individual's capacity (i.e. ability, awareness and understanding) likely requires context. If the demands of the evaluation do not adequately reflect the most challenging (or potentially injurious) tasks performed on a daily basis, any information collected may have limited application. For example, using an unloaded lifting task to assess an individual's risk of sustaining a lifting-related occupational injury may not be appropriate if the typical mechanism for injury involves high external loads. Injuries are sustained when an individual's demands exceed their capacity, and quite often it is the demands and not the task (e.g. lifting) itself that elicit the adapted movement behaviours that cause problems (Kulas et al., 2010, Van Dillen et al., 2008).

Dufek et al. (1995) proposed that the way an individual responds to varying demands ranges along a continuum from total accommodation to complete dismissal. The group theorized that the strategy chosen to perform a given task would depend on the recognition of its demands and the perceived severity of its potential effects on the body.

Although the primary basis for such an assertion was previous work documenting individual variation in impact forces while running (Bates et al., 1988, Bates et al., 1983) and landing (Caster and Bates, 1995, Dufek and Bates, 1990), a similar framework may be applicable to the study of movement patterns (i.e. kinematics). When presented with two tasks of the same pattern (e.g. lifting) but different demands (e.g. heavy versus light load), some individuals may perform both with a very similar movement strategy; others however, may adapt their movement behaviour and exhibit varying degrees of task demand dependence. For example, Flanagan and Salem (2008) found that amongst participants, a range of movement strategies were used to perform a squat, but interestingly, convergence was noted as the load increased from 25% to 100% of the three-repetition maximum. Although no mention was made to the variation amongst participants, McKean et al. (2010) also found that increasing the barbell load had a significant impact on the magnitude of hip and knee flexion used while squatting.

The degree to which a movement strategy is altered in response to an increased/decreased task demand may depend in part on the perception of risk as was suggested by Dufek et al. (1995); however, additional factors such as awareness, coordination and fitness (e.g. strength, endurance, cardiorespiratory efficiency) may be equally important. Speculating as to the exact reason why a pattern is changed would therefore be very difficult, particularly given the lack of evidence to support a homogeneous response across a group of participants. Faced with the task of picking up a pencil off the floor, highly astute, physically capable firefighters may not choose to adopt the same strategy as they would to lift a heavy piece of equipment, if the perception of the pencil task was such that it could not cause harm. On the other hand, highly astute firefighters with poor fitness may exhibit similar patterns for both tasks because they lack the strength necessary to perform the heavy lift in such a manner that would be perceived as “safe” or “good”; the demands of the task exceed their capacity to perform in a safe and effective manner. Using a similar argument, Savelberg et al. (2007) hypothesized that the age-related movement strategy differences noted previously (Papa and Cappozzo, 2000), may be partially explained by the load (demand)/capacity ratio. The authors manipulated the effort required (demand) to rise from a chair by applying various loads to the trunk (0-

45% body mass) and found that a 45% load increased trunk flexion and the hip extension moment and extended the total movement time. This work provides excellent insight into the extent to which the execution of a functional task like rising from a chair can be altered by elevating the task demands. However, perhaps even more valuable is the finding that the response appears comparable to that of an elderly population (lower capacity) who were asked to perform a less demanding (unloaded) variation of the same task (Papa and Cappozzo, 2000). It appears that individuals adapt their movement patterns in response to changes in the relationship between their demands and capacity.

Without a framework with which to describe a pattern as "good" or "bad", the way in which an individual responds to varying demands could arguably be viewed as secondary to simply acknowledging the fact that their movement patterns might be context specific. Whole-body movement screens, wherein individuals are asked to perform a battery of tasks, are frequently used to assess one's ability to perform various general patterns (e.g. squat, lunge) (Goss et al., 2009, Kiesel et al., 2007, Kiesel et al., 2010, Peate et al., 2007), yet little consideration is ever given to the possibility that a task's demands may influence the way an individual moves. Many of these screens comprise bodyweight patterns and individuals are instructed to perform in a slow, controlled manner, irrespective of the population being tested or the long-term rationale behind the evaluation. For example, the Functional Movement Screen™, a seven-task test created to evaluate joint mobility and stability (Cook et al., 2006a, Cook et al., 2006b), has been used as a means to predict injuries in athletes (Hoover et al., 2008, Kiesel et al., 2007, Schweim, 2009) and firefighters (Burton, 2006, Peate et al., 2007) and to guide recommendations for training (Goss et al., 2009, Kiesel et al., 2011), despite the fact that its tasks' demands may not provoke the adapted movement patterns that have been linked to the athletic or occupational injuries of interest. Therefore, the objective of this investigation was to determine whether individuals do in fact adjust their movement patterns in response to variation of the external load and speed of movement. Select patterns that have been previously linked to injury (e.g. spine motion (Callaghan and McGill, 2001, Lindsay and Horton, 2002, Marshall and McGill, 2010) and frontal plane knee motion (Chaudhari and Andriacchi, 2006, Hewett et al., 2005, Hewett et al., 2009)) were included in the investigation.

4.2. RESEARCH DESIGN AND METHODS

4.2.1. Experimental Overview

A repeated measures study design was used to evaluate the influence of load and movement speed on the execution of five whole-body tasks. Professional firefighters were recruited and asked to perform a battery of low-demand (i.e. light load, low movement speed) general whole-body tasks in random order, each chosen to replicate a fundamental movement pattern (i.e. lift, squat, lunge, push, pull). At no time were the objectives of the evaluation or the study hypotheses discussed with the participants. Once each task had been performed its demands were modified in three ways: 1) increased movement speed (through instruction); 2) increased external load; and 3) increased movement speed and external load. Select measures of motion were used to characterize the performance of each task and comparisons were made between conditions.

4.2.2. Participant Selection

Fifty-two professional firefighters (men) from the Pensacola Fire Department were recruited to participate in this investigation. All men were free of musculoskeletal injury or pain at the time of testing and were on full active duty. Their mean (SD) age, height and body mass were 37.7 (9.7) years, 1.81 (0.06) m and 92.1 (14.4) kg, respectively. The University's Office of Research Ethics, the Baptist Hospital Institutional Review Board and the City of Pensacola each approved the investigation and all participants gave their informed consent before the data collection began.

4.2.3. Task Selection

The tasks were chosen to reflect several commonly performed whole-body movement patterns (Figure 4.1). The five tasks were: 1) Lift – from standing, individuals lifted a box (0.33 x 0.33 x 0.28 m) to waist height and returned it to the ground; 2) Squat – from standing, individuals performed a bodyweight squat (depth was self-selected); 3) Lunge – from standing, individuals lunged forwards onto their right leg and returned to the starting position; 4) Push – from a staggered split stance (left leg forwards), individuals performed a standing cable press with the right arm; 5) Pull – from a staggered split stance (left leg forwards), individuals performed a standing cable pull with the right arm.

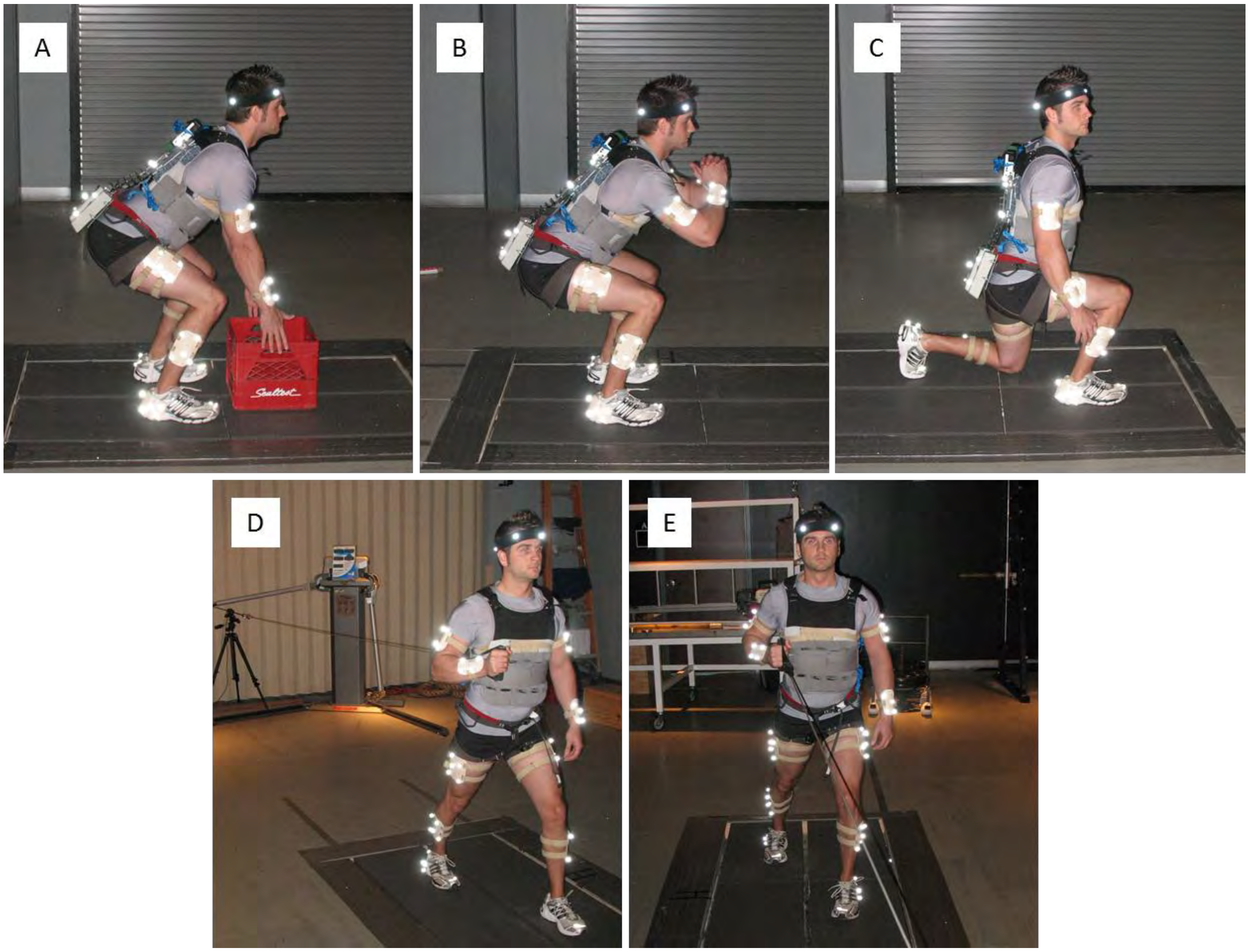


Figure 4.1. The A) Lift; B) Squat; C) Lunge; D) Push; and E) Pull tasks.

4.2.4. Experimental Protocol

Upon arrival, participants were instrumented with reflective markers and familiarized with the tasks they would be asked to perform using a standard set of instructions. The initial exposure to each task represented a low-demand scenario, whereby the external load and movement speed were low (LLLV – low load, low velocity). The lifting trials were performed with 6.8 kg, the squats and lunges were completed with bodyweight, and the push and pull loads (Keiser®, Fresno, CA, U.S.A.) were set at 4 kg (15 units on Keiser® display) and 6.5 kg (20 units), respectively. The five tasks were performed in a randomized fashion (three repetitions each) and approximately 15 s and 60 s of rest was given between each trial and task, respectively. If a participant failed to perform three repetitions correctly, an additional trial was performed after 15 s of rest. Once all tasks had been completed the movement speed and external load were modified in three ways: 1) low load, high velocity (LLHV) – increase in movement speed only; participants were asked to complete each trial as fast as was comfortable; 2) high load, low velocity (HLLV) – increase in external load only; the lifts were performed with 22.7 kg (NIOSH recommended maximum (Waters et al., 1993)), the squat and lunge trials were performed with an 18.2 kg weighted vest, and the push and pull loads were set at 9.8 kg (30 units) and 13.6 kg (40 units), respectively; 3) high load, high velocity (HLHV) – increase in movement speed and external load. Each condition was performed sequentially based on the expected musculoskeletal demands (i.e. LLLV → LLHV → HLLV → HLHV) so that systematic comparisons could be made across participants. No feedback was given regarding task performance at any point throughout the investigation. Compression shorts, a tight t-shirt and athletic shoes were worn at all times.

4.2.5. Data Collection and Signal Processing

Three-dimensional kinematic data were measured using a passive motion capture system (Vicon, Centennial, CO, U.S.A.). Reflective markers were placed on 23 anatomical landmarks to assist in defining the proximal and distal endpoints of the trunk, pelvis, thighs, shanks and feet. The hip joint centers (HJC) and knee joint axes (KJA) were also determined "functionally" using similar methods to those described by Begon et al. (2007) and Schwartz and Rozumalski (2005). Briefly, participants were asked to perform 10 repetitions of "hula-hooping" (closed-chain hip circumduction) and standing open-chain knee flexion/extension for the hip and knee joint computations, respectively. Visual 3D™ software (Version 4, C-Motion, Inc., Germantown, MD, U.S.A.) was used to calculate the axis of rotation between every pair of measured adjacent segment configurations. The most likely intersection and orientation of the axes were used to define the effective joint centers and joint axes, respectively. Using functionally defined segment endpoints for the shank and thigh has been shown to minimize the variation introduced via bony palpation (or digitization) and thus provide a more stable way to create each individual's rigid link segment model (Frost et al., 2012c). Sets of 4 or 5 markers, fixed to rigid pieces of plastic, were secured to each segment with Velcro® straps and used to track the position and orientation of each body segment in 3D space throughout the collection. However, each thigh segment was tracked with the pelvis and corresponding shank to minimize the influence of soft tissue motion artifact (Frost et al., 2012b). One static calibration trial (standing) was collected such that the orientation of each segment's local axis system, as defined by the anatomical markers or segment endpoints, could be determined via a transformation from an axis system embedded within each rigid body. The anatomical markers were removed once the calibration procedures were completed. The marker data was collected at 160 Hz, padded with one second of data (Howarth and Callaghan, 2009) using an end-point reflection method (Smith, 1989) and smoothed with a low-pass filter (4th order, dual pass Butterworth) with a cut-off frequency of 6 Hz (Winter, 2005).

4.2.6. Data Analyses

Participants' movement patterns were characterized with the nine variables described in Chapter 3. Each was chosen to either reflect a possible mechanism for injury (e.g. spine motion (Callaghan and McGill, 2001, Lindsay and Horton, 2002, Marshall and McGill, 2010) and frontal plane knee motion (Chaudhari and Andriacchi, 2006, Hewett et al., 2005, Hewett et al., 2009) or a coaching observation that is commonly used to differentiate individuals' performance (e.g. trunk angle relative to the vertical). Although these observations have not been cited as mechanisms for injury, each has been listed previously as a possible risk factor (Marras et al., 1993, Punnett et al., 1991) or shown to influence the knee, hip or low back moments while squatting (Fry et al., 2003, King et al., 2009) or lifting (Straker, 2003). The nine variables were: 1-3) spine flexion/extension (FLX), lateral bend (BND) and axial twist (TST) - the relative orientation of the trunk was expressed with respect to the pelvis (Woltring, 1991) and the corresponding direction cosine matrix was decomposed with an Euler rotation sequence of flexion/extension, abduction/adduction and axial rotation (Cole et al., 1993) to compute the spine angle about each axis. The orientation of the lumbar spine in a relaxed upright standing trial was defined as zero degrees; 4) trunk angle relative to the vertical (TRK) – the relative orientation of the trunk (flexion/extension only) was expressed with respect to an "imaginary" pelvis segment that was free to move with the body but constrained about the flexion/extension axis, thus remaining upright; 5) shank angle relative to the vertical (SHK) - the relative orientation of the left and right shank (flexion/extension only) was expressed with respect to the "imaginary" pelvis segment; 6) hip to ankle distance (HIP) – using the "imaginary" pelvis described above to define a body-fixed anterior/posterior (A/P) axis, the position of each hip joint in the A/P direction was described relative to the same side ankle (mid-point of medial and lateral anatomical landmarks); 7) knee to ankle distance (KNE) - the position of each knee joint in the A/P direction was described relative to the same side ankle; and 8-9) left (LFT) and right knee (RGT) position relative to the frontal plane – the position of each knee joint in the medial/lateral direction was described relative to a body-fixed plane created using the corresponding hip joint, ankle joint and distal foot (mid-point of medial and lateral anatomical landmarks). The SHK, HIP and KNE variables were only computed for the lead leg of the lunging (right), pushing (left) and pulling (left) tasks and defined as an average of the left and right sides for lifting and squatting. Figure 4.2 provides a visual representation of each variable as it relates to the five tasks.

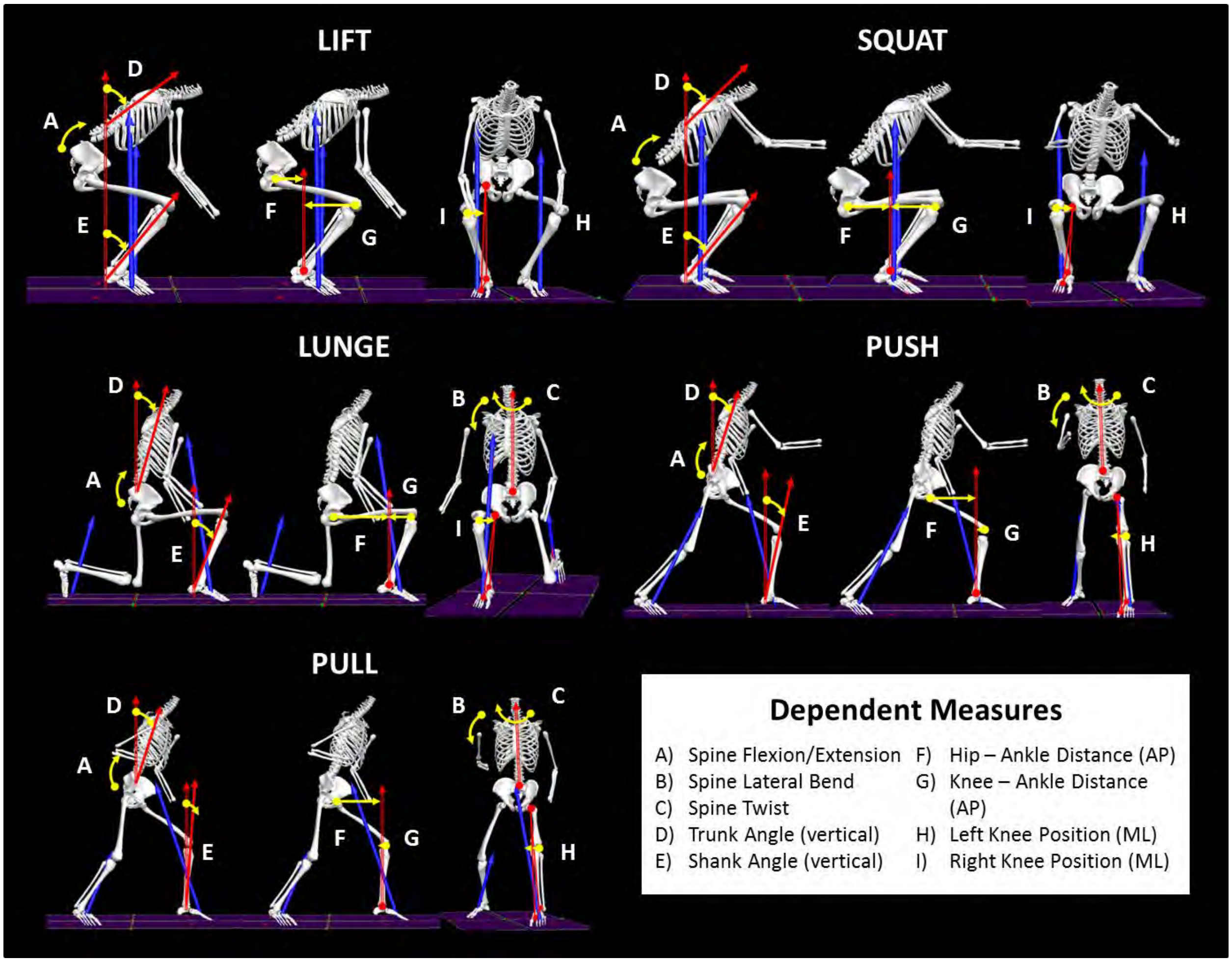


Figure 4.2. Participants` movement patterns were characterized with the following variables: A) spine flexion/extension (flexion → +); B) spine lateral bend (bend right → +); C) spine axial twist (twist right → +); D) trunk angle (forward → +); E) shank angle (forward → +); F) hip-ankle distance (anterior → +); G) knee-ankle distance (anterior → +); H) left knee position (lateral → +); I) right knee position (medial → +).

To objectively define the start, mid-point and end of each trial, event detection algorithms were created in Visual 3D™ by tracking the motion of the trunk, pelvis, right forearm (push and pull) and whole-body center of mass (COM). Each task was separated into two phases; a descent and ascent for the lifting, squatting and lunging tasks, and a "towards" and "away" from the body (in reference to motion of the right forearm) for the push and pull. To verify that events were defined as intended, model animations of all trials were inspected visually. Maximums, minimums and means were computed for the nine dependent variables (each phase separately) and the data series were normalized to twenty samples so that time-series comparisons could be made. The "peak" of each variable, with the exception of BND and TST, was described as the deviation (maximum or minimum) hypothesized to be most relevant to the characterization of each pattern (i.e. FLX – flexion, TRK and SHK – forward bend, HIP – posterior displacement, KNE – anterior displacement, LFT and RGT – medial displacement). Peak BND and TST were described as the range (i.e. max – min) observed for the specified phase.

4.2.7. Statistical Analyses

The three-repetition means for each condition were used to examine the influence of load and speed on each dependent measure. Comparisons were made using a general linear model with two repeated factors (IBM SPSS Statistics, Version 20.0, Armonk, NY, U.S.A.). Significant main effects and load x speed interactions were described by a p-value level less than 0.05.

Within-Subject Differences

Subject-specific responses for select dependent measures (i.e. those cited as possible mechanisms for injury; FLX, BND, TST, LFT and RGT) were examined for each task using an approach similar to that described in Chapter 3. The mean of both light load conditions (i.e. low and high velocity) was compared to that of the high load conditions and the difference score was normalized by the maximum within-subject variation (group average) ± 1SD observed for any metric (i.e. max, min or mean) or condition of that particular variable. A score greater than one or less than negative one implied that the load effect was greater than the variation observed within participants ± 1SD, and thus was defined herein as a biologically significant or "meaningful" difference (Chapter 3). Using the *maximum* within-subject variation observed for any metric provided a more conservative estimate of the boundary conditions with which a "meaningful" difference was defined, in comparison to the method outlined in Chapter 3. This process was repeated to examine the impact of movement speed; the mean of both low velocity conditions (i.e. low and high load) was compared to that of the high velocity conditions and the difference scores were normalized by the within-subject variation used previously. As such, the same difference score was used to define a “meaningful” subject-specific response with regards to changes in the load or speed of movement.

4.3. RESULTS

Significant main effects of load and speed were noted for several of the variables chosen to characterize the motion of each task (Table 4.1). However, each dependent measure was not influenced to the same degree or in the same manner (increase or decrease) across the five tasks being investigated, nor were they affected by changing the external load and movement speed in the same way. For example, when participants performed the lifting task with a heavier load, they adopted a more upright trunk posture, which was characterized by a decrease and increase in their trunk and shank angles, respectively. Increasing the speed of movement however, prompted the opposite response; participants were found to use a more “hip dominant” pattern, whereby their hips and knees were shifted backwards. Similar adaptations were observed when the squat was performed with a higher load and speed (i.e. load – hips forwards; speed – hips backwards). For the lunge, push and pull, the load and speed were found to have a comparable influence on participants’ movement patterns, albeit dissimilar for each task. The lunges were performed with more spine flexion, a greater trunk lean and an anterior shift of the knee. Pushing and pulling were both characterized by an increase in spine lateral bend and forward trunk lean, but while participants sat back (i.e. hips posterior) during the higher demanding pull trials, they exhibited a forward shift (i.e. knees anterior) when pushing. A summary of all findings for each variable and task is described in Appendix B.

Table 4.1. A statistical summary of all main effects (load and speed) and interactions (load x speed) for the lift (LFT), squat (SQT), lunge (LNG), push (PSH) and pull (PLL) tasks. Results for the peaks and means of each phase (e.g. descent and ascent) are presented. Significant main effects ($p<0.05$) are highlighted by an ↑ or ↓; the direction indicates whether more or less motion was observed following an increase to the demands. Significant interations ($p<0.05$) are marked with a '#'. N/A signifies not computed.

		PHASE 1										PHASE 2									
		PEAK					MEAN					PEAK					MEAN				
		LFT	SQT	LNG	PSH	PLL	LFT	SQT	LNG	PSH	PLL	LFT	SQT	LNG	PSH	PLL	LFT	SQT	LNG	PSH	PLL
LOAD	FLX		#	↑	#			#	↑	↓	↑		#	↑				#	↑	↓	↑
	BND	N/A	N/A		↑	↑	N/A	N/A	↓	#	#	N/A	N/A		↑	#	N/A	N/A		↑	↑
	TST	N/A	N/A	↓	#	#	N/A	N/A		↓	↑	N/A	N/A		↑	#	N/A	N/A	↓	#	↑
	TRK	↓		↑	↑	↑			↑	↑	#	↓	#	↑	↑	#		#	↑	↑	↑
	SHK	↑		↑	↑		↑		#	↑	↑			#	↑		↓		#	↑	
	HIP		↓			↑		↓	#		#	#	#			#	↑	↓	#		#
	KNE			↑	↑		↑		#	↑	↓			#	↑		↓		#	↑	
	LFT			N/A	#	↑			N/A	↕		#		N/A	↓		#		N/A	↓	
	RGT	#		↓	N/A	N/A		#	#	N/A	N/A	#		↓	N/A	N/A			↓	N/A	N/A
SPEED	FLX		#	↑	#	↑	↓	#	↑	↓	↑		#	↑	↑	↑		#	↑		↑
	BND	N/A	N/A	↑	↑	↑	N/A	N/A		#	#	N/A	N/A	↑	↑	#	N/A	N/A	↑	↑	↑
	TST	N/A	N/A	↑	#	#	N/A	N/A		↑		N/A	N/A	↑	↑	#	N/A	N/A		#	↓
	TRK			↑		↑		↓	↑		#		#	↑		#	↑	#	↑	↑	↑
	SHK		↓	↑	↑	↑		↓	#	↑	↑		↓	#	↑	↑			#	↑	↑
	HIP	↑	↑	↑		↑			#		#	#	#	↑		#			#		#
	KNE	↓	↓	↑	↑	↑		↓	#	↑	↑		↓	#	↑	↑			#	↑	↑
	LFT			N/A	#	↑		↓	N/A	#	↑	#		N/A		↑	#		N/A	↓	↑
	RGT	#			N/A	N/A		#	#	N/A	N/A	#			N/A	N/A				N/A	N/A

FLX – spine flexion/extension; BND – spine lateral bend; TST – spine twist; TRK – trunk angle; SHK – shank angle; HIP – hip to ankle distance; KNE – Knee to ankle distance; LFT – left knee position; and RGT – right knee position

The subject-specific adaptations to an increased load are illustrated in Figure 4.4. Substantial variation was observed in the magnitude and direction of the responses observed amongst participants for each of the variables investigated. Most were smaller in magnitude than the between-trial variation observed amongst participants (i.e. not "meaningful"); however, with the exception of LFT for the pushing tasks, at least one firefighter was found to exhibit a "meaningful" change in the positive (less motion) and negative direction (more motion) for every dependent measure. This finding highlights the fact that although there were significant load effects seen for the group, the mean adaptations did not reflect the movement-related changes exhibited by each individual. That said, in comparison to the number of positive “meaningful” changes, there were more participants who demonstrated an increase in spine and frontal plane motion when the load was elevated (125 versus 39 and 113 versus 55 for phase one and two, respectively).

Similar subject-specific adaptations were seen in response to increasing the movement speed (Figure 4.5); however, in contrast to the single case cited above, there were seven instances wherein at least one participant did not exhibit a positive “meaningful” change; LFT for squatting, FLX for lunging, BND, TST and LFT for pushing, and TST and LFT for pulling. Generally, increasing the movement speed did have a greater negative effect on the spine and frontal plane knee motion adopted while performing the five tasks, in comparison to increasing the load - the total number of “meaningful” negative and positive changes observed in response to an increase in speed were 246 versus 25 and 201 versus 27 for phase one and two, respectively. Also of note was the finding that of the 52 participants, 20 exhibited a “meaningful” change in FLX while squatting; 10 improved and 10 got worse, thus making it difficult to make any general conclusions or group recommendations. This result is further highlighted by the model animations in Figure 4.5; the LLLV condition for participant one appears very similar to the LLHV condition for participant two.

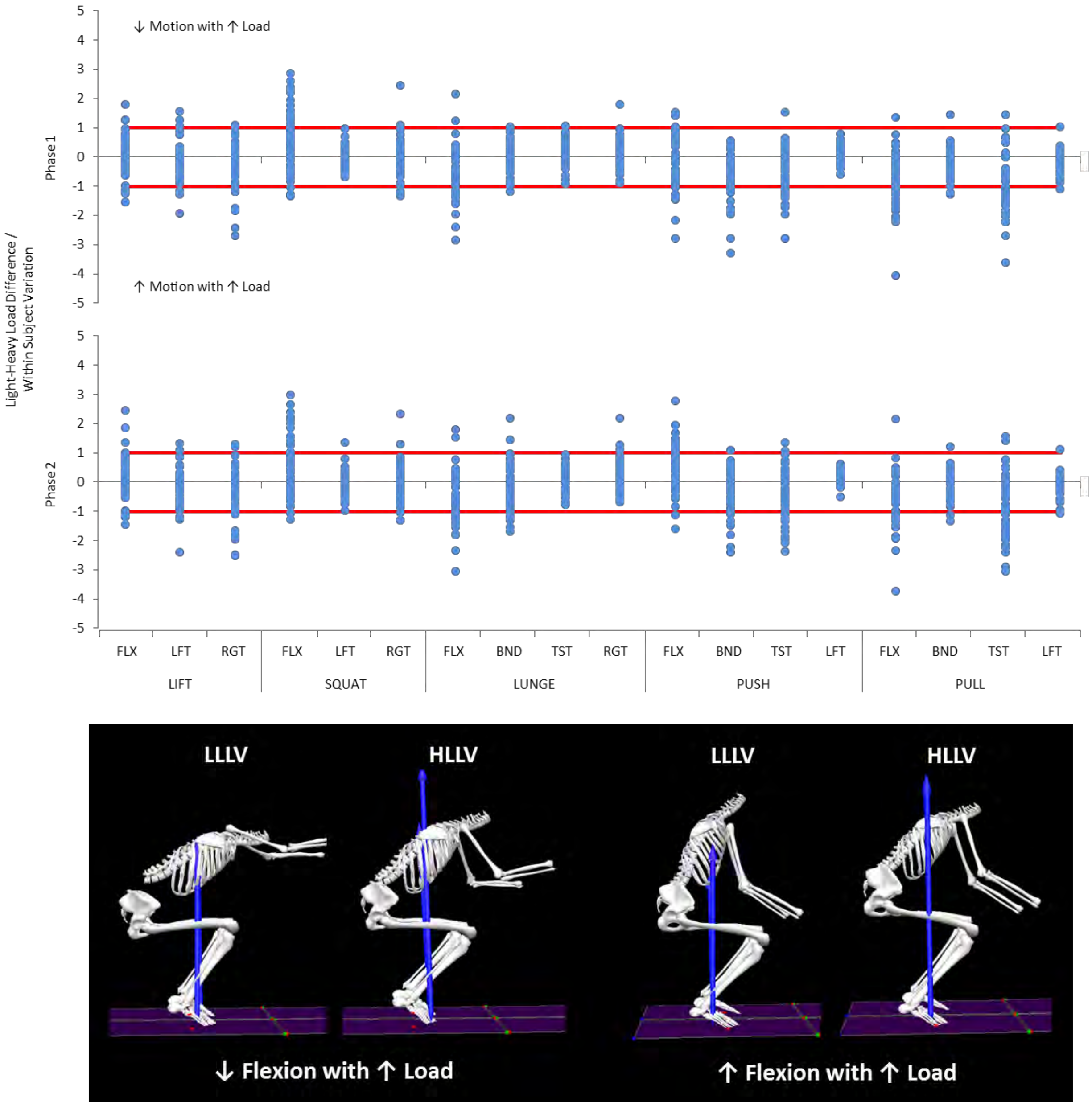


Figure 4.3. Individual responses in spine and knee motion to an increase in LOAD. The mean of the low (low and high velocity) and high load conditions were compared and the difference score was normalized by the maximum within subject variation ± 1SD observed for any metric (i.e. max, min or mean) or condition of a particular variable (e.g. spine flexion/extension) and task. The data presented represent differences in the peak of each variable and phase (e.g. descent and ascent). The solid red lines denote a difference score equal to the within subject variation ± 1SD. Values outside of these boundaries were described as "meaningful" changes. A positive response implies a *decrease* in motion with an *increase* in load. The model animations (squat) for two participants are presented to provide a visual depiction of the variation observed in spine flexion, trunk posture and the hip and knee positions.

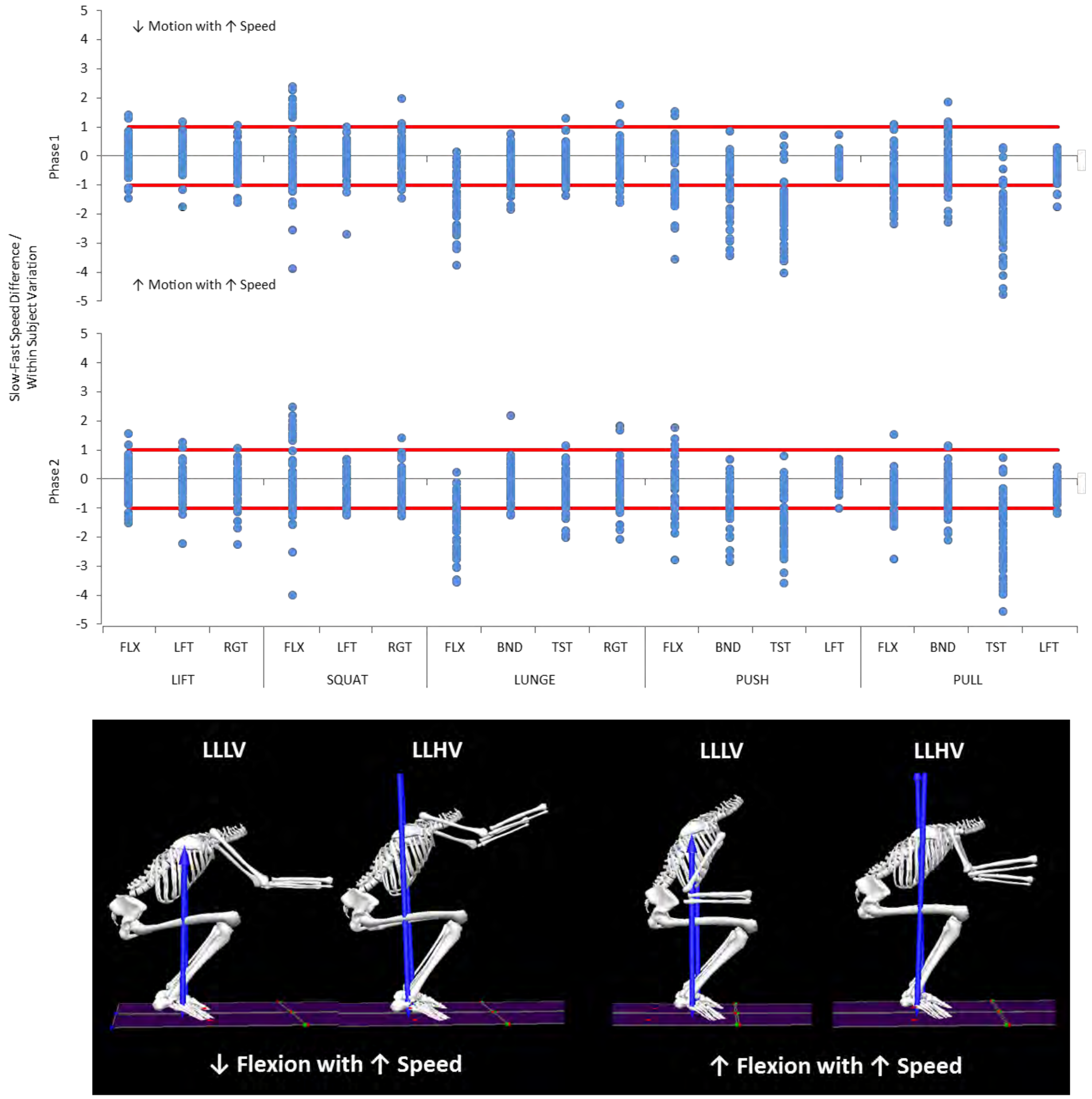


Figure 4.4. Individual responses in spine and knee motion to an increase in SPEED. The mean of the low (low and high load) and high velocity conditions were compared and the difference score was normalized by the maximum within subject variation ± 1SD observed for any metric (i.e. max, min or mean) or condition of a particular variable (e.g. spine flexion/extension) and task. The data presented represent differences in the peak of each variable and phase (e.g. descent and ascent). The solid red lines denote a difference score equal to the within subject variation ± 1SD. Values outside of these boundaries were described as "meaningful" changes. A positive response implies a *decrease* in motion with an *increase* in speed. The model animations (squat) for two participants are presented to provide a visual depiction of the variation observed in spine flexion, trunk posture and the hip and knee positions.

4.4. DISCUSSION

The findings from this investigation provide overwhelming support for the notion that, for any number of reasons (e.g. perception of risk, fitness, coordination, awareness), individuals adapt their movement patterns in response to the demands of a task. However, perhaps more intriguing was the fact that the adaptations observed were quite variable amongst participants, and often specific to the task or type of demand (i.e. load or speed) in question.

Faced with the seemingly simple task of lifting a box from the ground, the group adapted their movement patterns in response to an increase in load; the trunk angle (i.e. lean) was found to be significantly lower during the heavy trials (even during the descent phase before the load was placed in the hands!). Whether participants made a conscious decision to change or not, an upright trunk posture is often perceived as one of the most effective solutions to accommodate an elevated demand while lifting because the individual is better positioned to "lift with their legs and not with their back". However, lifting with an upright trunk posture does not guarantee that a neutral lumbar spine curvature will be maintained, nor does it imply that less mechanical work will be done by the low back moment of force (consider the effort required as the elbows and shoulders are extended to allow the object to clear the knees). It does, however, make it difficult and possibly unnecessary to engage the hip extensors given that the hip moment demands are attenuated when the joints are positioned directly beneath the trunk and over the base of support. As a result, choosing to lift "…not with the back" may have little impact on the risk of sustaining a low back injury (spine posture may be critical) and could inadvertently increase the demand imposed on the knees. If the body is viewed as a set of rigid linked segments it is a physical impossibility to lift with an upright torso when the hips are positioned posterior to the base of support (barring the use of a counterbalance). To accommodate a vertically oriented trunk, the shank(s) must be angled forward, which then shifts the knees and hips forwards. As a general rule, many practitioners will recommend a lifting or squatting pattern, wherein the trunk and shank segments are kept parallel throughout the range of motion, thereby allowing both the hip and knee extensors to contribute to the effort being made. It is worth noting that the participants chose (consciously or subconsciously) an opposing movement strategy to accommodate the increase in speed; the hips and knees were positioned further backwards (i.e. a more "hip dominant" strategy) and they increased their forward trunk lean.

Given the lack of homogeneity within the group, it would be inappropriate to speculate as to a single reason why participants responded differently to the high speed lifting trials. However, the possibilities are intriguing given that a similar mean response was noted for the squat. Instructing the firefighters to perform as fast as was comfortable may have shifted their attentional focus (Wulf and Prinz, 2001) from their body posture and motion during task execution (i.e. internal focus) to the speed at which it was performed (i.e. external focus), perhaps causing them to ignore any preconceived ideas regarding the most effective or safest way to move. They no longer focused on *how* the task was executed but instead shifted their attention to *how fast* they were performing. In comparison, it is unlikely that the instruction to "lift the heavy box" would have had the same influence on the participants' focus of attention, unless the load was of a magnitude that required a maximal or supra-maximal effort (i.e. at or above their personal capacity). Faced with the fear of failing to perform, participants might shift their attention to the load being lifted and away from the way they move, if in fact they were consciously considering their movement strategies in the first place. Numerous studies have shown that shifting an individual's focus of attention can influence movement outcomes (Peh et al., 2011). Alternatively, the firefighters may have simply found it easier to lift and squat quickly when they adopted a more hip dominant strategy. If the hips are positioned posteriorly and able to contribute to the work being done less effort will be required by the extensors of the knees, which consequently, will also reduce the joint loads and perhaps even the potential for injury. When the trunk is kept upright it also becomes very difficult to squat or lift to any substantial depth while keeping the heels on the ground (consider the link between segments), hence the "toe squatter". Participants adopting this movement strategy during the slow trials may have found it too difficult to perform quickly with a smaller base of support.

The lunge trials were executed by displacing the body's center of mass in the anterior/posterior and vertical directions, which for most participants, would have increased their body's momentum and thus the level of effort and coordination required, in comparison to performing a lift or squat. Firefighters lacking the awareness or understanding needed to perform safely and effectively would be expected to exhibit a movement behaviour indicative of these additional demands (e.g. uncontrolled forward motion), particularly during the transition from the descent to ascent phase when the effort required is highest. Changing the lunge's demands via an increase in load or speed would simply make it even more challenging to control the body's forward momentum. This is precisely what the group's adapted behaviour looked like in response to the elevated demands; they showed significantly ($p<0.05$) more lumbar spine flexion and forward trunk lean, and an anterior shift of the knee. Because the load was increased via a weighted vest participants may have found it more difficult to control their trunk due to the increased "core" and whole-body stability demands; however, it is also possible that the changes were planned and made in preparation to "throw" their trunks backwards to assist with the ascent phase.

Resisting lumbar spine rotation during a bilateral push-up is relatively simple because forces are applied to the ground on either side of the body's midline; each arm offsets the rotational demands created by placement of the other. However, if one arm were raised, the individual's ability to avoid motion in the transverse plane would be challenged because of the single off-centre force now imposing a rotational demand on the body. The farther the hand from the midline, the more challenging the task becomes. This is why, if asked to perform a single arm push-up, individuals accommodate by shifting their upper body over their hand. It also rationalizes the increase in lateral bend exhibited by the group in response to elevating the push and pull loads or speeds.

An individual's movement patterns provide us with potential insight into their abilities, preferences, awareness and understanding, collectively. It becomes exceedingly difficult to evaluate a specific ability (e.g. flexibility) if the individual's task performance was also influenced by their perception of risk, appreciation for the task's objectives, previous experiences or level of awareness. Assuming that someone moves in a given manner because of any one factor is likely inappropriate in most settings as it could skew the interpretation of the observations and misdirect any recommendations being made to improve their safety or effectiveness. The groups' adapted movement behaviour could be rationalized for each task using fundamental principles of biomechanics, but each participant was also different, and thus adapted their movement patterns for reasons specific to their capacity and prior experiences. There were certainly individuals who exhibited a similar response to that of the group; however, at least one firefighter was found to exhibit a biologically significant or "meaningful" adaptation in either direction (positive or negative) for all but one variable investigated. Movement screening or the assessment of a particular pattern would be much simpler if everyone responded to a task's demands in a similar manner, but such is not the case, as was illustrating by the model animations in Figures 4.4 and 4.5.

From a fundamental injury standpoint, tissues fail when their tolerance is exceeded by the applied load. If an individual's movement patterns are being evaluated to establish risk or personalize recommendations to prevent the occurrence of future problems, it will likely be important to first identify the possible mechanisms for the injuries of interest so that "key features" of the motion pattern can be used as criteria with which to describe a movement as "good" or "bad". For example, the most common injuries sustained by firefighters are those to the lower back, knees and shoulders, which suggests that adopted patterns such as uncontrolled spine and frontal plane knee motion may be critical observations. Obviously the demands of the task will influence the applied load and therefore the potential for sustaining an injury; however, this approach could provide a framework with which to categorize individuals' responses to varying demands while accommodating the potential interaction between ability, awareness and understanding. The exact reason as to why the movement pattern was exhibited may not be as important as noting its presence (at least initially), given that simply providing feedback, coaching or asking whether the individual was aware may alleviate the issue.

As has been highlighted by the results of this investigation, individuals adapt their movements in response to increased external task demands. Whether because the elevated challenge provoked a sense of risk motivating the adoption of a safer and more effective (perceived) pattern, or was of a magnitude that exceeded capacity causing compensatory motion, the information gained by evaluating movement can provide valuable insight to assist in making future recommendations for training. But perhaps there is a load, speed, number of repetitions, time, etc. for each of us at which we compensate, or demonstrate one or more of the "key features" that have been identified as critical observations for a particular task. Training could then be viewed as a means to elevate the magnitude of demands (e.g. load, speed, etc.) at which these movement patterns are observed, via changes to our ability, understanding or awareness (i.e. capacity), such that we are able to perform all job- and life-related physical activities in a safe and effective manner.

4.5. CONCLUSIONS

Simply because an individual exhibits the ability to perform a low-demand task does not imply that they will also be physically prepared to perform safely or effectively when the task's demands are increased. Nor does it imply the opposite. Having superior strength will provide greater opportunity to perform a high intensity activity, just as muscular endurance will assist when a task's duration is extended, but these physical attributes only reflect potential. Other factors such as the perception of risk, awareness and coordination can also influence the way that we move and thus any adaptations observed in response to a change in demands will likely be quite variable amongst a group of individuals, and specific to the task or type of demand in question. This is precisely what was found amongst the firefighters in this study; a range of movement patterns were exhibited in response to increasing the external load or speed of movement and the adapted behaviors were demand-specific. During the first phase of each task, there were 125 "meaningful" negative adaptations (i.e. more spine or frontal plane knee motion) observed in response to using a heavier load, but 246 when participants were instructed to perform with a higher speed. As a result, movement evaluations comprising only low demand activities may not adequately reflect an individual's capacity, or their risk of injury, and could skew any recommendations being made for training.

Chapter 5

INVESTIGATION THREE

THE PREDICTIVE VALUE OF GENERAL MOVEMENT TASKS IN ASSESSING OCCUPATIONAL TASK PERFORMANCE

5.1. INTRODUCTION

With regards to the evaluation of movement, task specificity implies that an individual's performance on one task cannot be used to describe their execution of another (Baker et al., 1994). Attempts to generalize may lead to inaccurate characterizations (e.g. high risk) and inappropriate recommendations for training. Given that our perceptions and previous experiences influence the way we move (Dufek et al., 1995) it is difficult to argue against the notion of specificity, but rarely, in the context of evaluating an individual's movement patterns, is it even considered. Efforts are made to establish individuals' overall risk of injury using whole-body screens comprising non-specific tasks (e.g. squat, lunge) (Kiesel et al., 2007, Mottram and Comerford, 2008, Peate et al., 2007) that may not reflect the activities most likely to cause an injury in one's life (job). Musculoskeletal injuries account for approximately half of all fireground injuries sustained by firefighters (Karter Jr and Molis, 2010), but to date there is no evidence to suggest that the movement strategies used to execute any of the complex job-specific skills could be captured with a general evaluation. There is also no evidence to the contrary.

Although very little is known about task specificity as it relates to movement, many researchers have suggested that an individual's performance (e.g. strength) on two seemingly similar exercises may not be related (Baker, 1996, Baker et al., 1994, Blazevich et al., 2002, Carlock et al., 2004, Cotterman et al., 2005). For example, correlations of 0.55 and 0.11 were reported between the squat and the hack squat (machine-based exercise) (Blazevich et al., 2002) and the squat and the vertical jump (Baker, 1996), respectively, which led the authors to state that movement pattern specificity should be considered when testing. These findings cannot be used as direct evidence to support the notion of movement specificity, but they do provide a rationale as to why one might question the efficacy of generalizations. That said, gauging an individual's ability to coordinate their body in space with performance metrics such as a one repetition maximum squat may simply be inappropriate; amongst individuals with no reported history of movement-related instruction, performance and movement quality, as defined by explicit criteria, appear to be independent attributes (Burton, 2006, Frost et al., 2012a, Okada et al., 2011).

In an ideal world, an individual's capacity would be evaluated within the context of their life's demands, or more specifically, in relation to relevant activities that may impose risk. Firefighters would be observed while performing job-specific skills such as pulling hose, forcing entry or extricating victims from a building, and their movement strategies would be quantified and used in combination with knowledge of hypothesized or demonstrated injury mechanisms to estimate risk. But such an approach is not always possible or practical (given limited resources), and thus generalizing to some degree might be necessary amongst certain populations (it may also help establish standards). In the event that a specific task is identified as high-risk within a particular demographic (e.g. jump landing in women) and there are hypothesized injury mechanisms with which to compare individuals' movement strategies, the specific task should arguably be included in all future evaluations for that population. The occurrence of anterior cruciate ligament (ACL) injury has been predicted, in part, by evaluating individuals' movement patterns during the performance of injury-causing activities (Hewett et al., 2005); however, most researchers and practitioners continue to use general, non-specific tasks to categorize and describe individuals' movement competency. There would likely be tremendous value in using such an approach, although in the absence of a scientific basis the application of any findings will be limited. Therefore, the objective of this study was to investigate the degree to which a battery of general tasks could be used to describe the movement patterns employed by firefighters to perform their job-specific skills. An emphasis was placed on select descriptors of motion that have been previously cited as possible risk factors for injury (i.e. spine motion (Callaghan and McGill, 2001, Lindsay and Horton, 2002, Marshall and McGill, 2010) and frontal plane knee motion (Chaudhari and Andriacchi, 2006, Hewett et al., 2005, Hewett et al., 2009).

5.2. RESEARCH DESIGN AND METHODS

5.2.1. Experimental Overview

A repeated measures study design was used to investigate the degree to which general whole-body tasks could be used to describe the execution of select occupation-specific skills. Professional firefighters were recruited and asked to perform a battery of general (i.e. lift, squat, lunge, push and pull) and occupation-specific (i.e. chop, forced entry, hose drag, hose pull, heavy drag) tasks that simulated the demands of firefighting. Each general task was performed with four combinations of load (low and high) and speed (low and high) to accommodate the potential influence of a task's demands on the degree of task specificity. Select descriptors of motion that have been previously cited as possible mechanisms of injury were compared across tasks.

5.2.2. Participant Selection

Fifty-two professional firefighters (men) from the Pensacola Fire Department were recruited to participate in this investigation. All men were free of musculoskeletal injury or pain at the time of testing and were on full active duty. Their mean (SD) age, height and body mass were 37.7 (9.7) years, 1.81 (0.06) m and 92.1 (14.4) kg, respectively. The University's Office of Research Ethics, the Baptist Hospital Institutional Review Board and the City of Pensacola each approved the investigation and all participants gave their informed consent before the data collection began.

5.2.3. Task Selection

The general tasks were chosen to reflect several commonly performed whole-body movement patterns (Figure 5.1). The five tasks were: 1) Lift – from standing, individuals lifted a box (0.33 x 0.33 x 0.28 m) to waist height and returned it to the ground; 2) Squat – from standing, individuals performed a bodyweight squat (depth was self-selected); 3) Lunge – from standing, individuals lunged forwards onto their right leg and returned to the starting position; 4) Push – from a staggered split stance (left leg forwards), individuals performed a standing cable press with the right arm; 5) Pull – from a staggered split stance (left leg forwards), individuals performed a standing cable pull with the right arm.

Given that professional firefighters were recruited to participate in this investigation, each occupation-specific task was designed to simulate a specific demand of firefighting (Figure 5.1). The five tasks were: 1) Chop – individuals struck an object lying on the ground with a 4.5 kg sledgehammer (direction of swing was self-selected); 2) Forced entry – individuals struck a ceiling-mounted “heavy bag” with a 4.5 kg sledgehammer (direction of swing was self-selected); 3) Hose drag – a 6.4 cm diameter rope, connected to a cable machine (Keiser®, Fresno, CA, U.S.A.) was placed over the right shoulder and held across the body. Participants were instructed to initiate forward movement from a staggered stance (left foot forwards); 4) Hose pull – a 6.4 cm diameter rope was pulled approximately 5 m in a hand-over-hand fashion. Resistance was applied via a cable (Keiser®, Fresno, CA, U.S.A.) attached to the end of the rope; 5) Heavy drag – a weighted sled was pulled approximately 5 m.

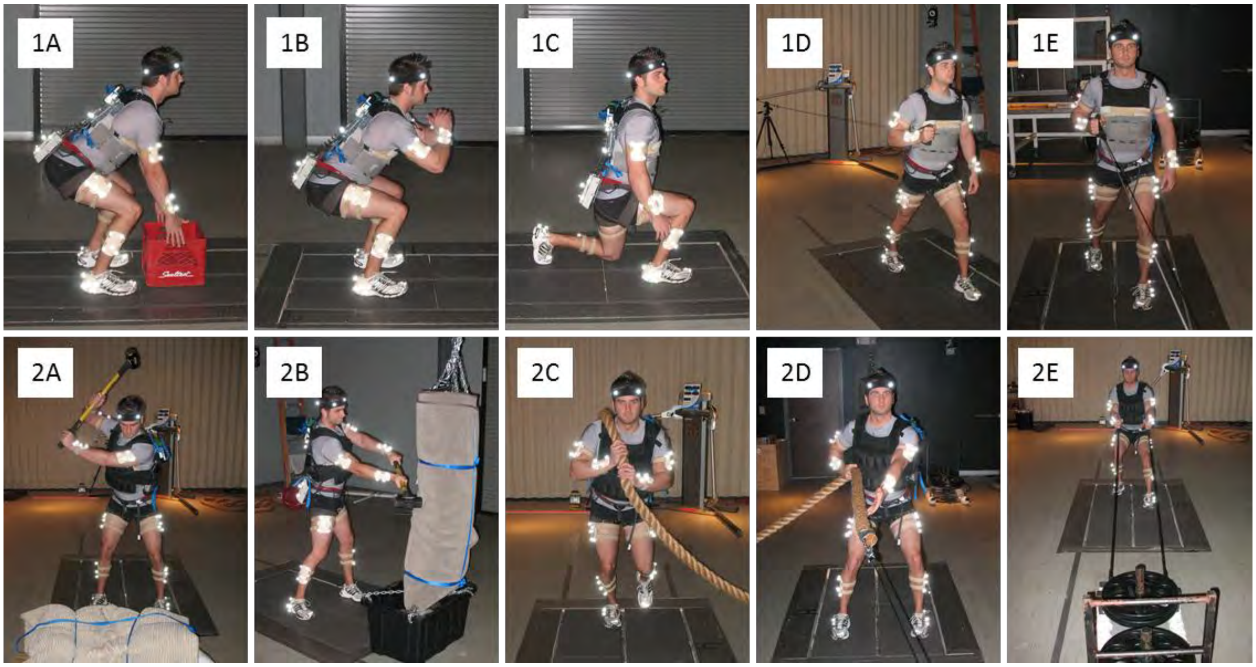


Figure 5.1. The general movement patterns (1A – Lift; 1B – Squat; 1C – Lunge; 1D – Push; and 1E – Pull) and job-specific tasks (2A – Chop; 2B – Forced entry; 2C – Hose drag; 2D – Hose pull; and 2E – Heavy drag).

5.2.4. Experimental Protocol

Upon arrival, participants were instrumented with reflective markers and familiarized with the tasks they would be asked to perform using a standard set of instructions. Because a task's demands have been shown to impact the way that individuals move (Chapter 4), participants were asked to perform each general task with two external loads and at two movement speeds. The initial exposure to each task represented a low-demand scenario, whereby the external load and movement speed were low (LLLV – low load, low velocity). The lifting trials were performed with 6.8 kg, the squats and lunges were completed with bodyweight, and the push and pull loads (Keiser®, Fresno, CA, U.S.A.) were set at 4 kg (15 units on Keiser® display) and 6.5 kg (20 units), respectively. The five tasks were performed in a randomized fashion (three repetitions each) and approximately 15 s and 60 s of rest was given between each trial and task, respectively. If a participant failed to perform three repetitions correctly an additional trial was performed after at least 15 s of rest. Once all tasks had been completed the movement speed and external load were modified in three ways: 1) low load, high velocity (LLHV) – increase in movement speed only; participants were asked to complete each trial as fast as was comfortable; 2) high load, low velocity (HLLV) – increase in external load only; the lifts were performed with 22.7 kg (NIOSH recommended maximum (Waters et al., 1993)), the squat and lunge trials were performed with an 18.2 kg weighted vest, and the push and pull loads were set at 9.8 kg (30 units) and 13.6 kg (40 units), respectively; 3) high load, high velocity (HLHV) – increase in movement speed and external load. Each condition was performed sequentially based on the expected musculoskeletal demands (i.e. LLLV → LLHV → HLLV → HLHV).

Following the completion of the HLHV condition, participants were asked to perform the firefighting tasks in random order. As described above for the general tasks, three trials of each simulated firefighting skill were performed and approximately 15 s and 60 s of rest was given between each trial and task, respectively. To better simulate the occupational demands of the chop and forced entry tasks, five repetitions were performed within each trial. If participants failed to perform correctly an additional trial was performed after at least 15 s of rest. A weighted vest (18.2 kg) was worn throughout this phase of testing to simulate the mass of a firefighter's personal protective equipment. The two hose handling tasks were resisted with 9.8 kg (30 units on Keiser® display) and the mass of the sled was set at 81.8 kg. Three-trial means for each task were used in the analyses. No feedback was given regarding task performance at any point throughout the investigation. Compression shorts, a tight t-shirt and athletic shoes were worn at all times.

5.2.5. Data Collection and Signal Processing

Three-dimensional motion data was measured using a passive motion capture system (Vicon, Centennial, CO, U.S.A.). Reflective markers were placed on 23 anatomical landmarks to assist in defining the proximal and distal endpoints of the trunk, pelvis, thighs, shanks and feet, although the hip joint centers (HJC) and knee joint axes (KJA) were also determined "functionally" using similar methods to those described by Begon et al. (2007) and Schwartz and Rozumalski (2005). Briefly, participants were asked to perform 10 repetitions of "hula-hooping" (closed-chain hip circumduction)and standing open-chain knee flexion/extension for the hip and knee joint computations, respectively. Visual 3D™ software (Version 4, C-Motion, Inc., Germantown, MD, U.S.A.) was used to calculate the axis of rotation between every pair of measured adjacent segment configurations. The most likely intersection and orientation of the axes was used to define the effective joint centers and joint axes, respectively. Using functionally defined segment endpoints for the shank and thigh has been shown to minimize the variation introduced via bony palpation (or digitization) and thus provide a more stable way to create each individual's rigid link segment model (Frost et al., 2012c). Sets of 4 or 5 markers, fixed to rigid pieces of plastic, were secured to each segment with Velcro® straps and used to track the position and orientation of each body segment in 3D space throughout the collection. However, each thigh segment was tracked with the pelvis and corresponding shank to minimize the influence of soft tissue motion artifact (Frost et al., 2012b). One static calibration trial (standing) was collected such that the orientation of each segment's local axis system, as defined by the anatomical markers or segment endpoints, could be determined via a transformation from an axis system embedded within each rigid body. The anatomical markers were removed once the calibration procedures were completed. The marker data was collected at 160 Hz, padded with one second of data (Howarth and Callaghan, 2009) using an end-point reflection method (Smith, 1989) and smoothed with a low-pass filter (4th order, dual pass Butterworth) with a cut-off frequency of 6 Hz (Winter, 2005).

5.2.6. Data Analyses

Participants' movement patterns were characterized with five variables, each chosen to reflect a coaching observation that has been previously cited as a possible mechanism for injury (e.g. spine motion (Callaghan and McGill, 2001, Lindsay and Horton, 2002, Marshall and McGill, 2010) and frontal plane knee motion (Chaudhari and Andriacchi, 2006, Hewett et al., 2005, Hewett et al., 2009)). The five variables were: 1-3) spine flexion/extension (FLX), lateral bend (BND) and axial twist (TST) - the relative orientation of the trunk was expressed with respect to the pelvis (Woltring, 1991) and the corresponding direction cosine matrix was decomposed with a rotation sequence of flexion/extension, abduction/adduction and axial rotation (Cole et al., 1993) to compute the spine angle about each axis. The orientation of the lumbar spine in a relaxed upright standing trial was defined as zero degrees; and 4-5) left (LFT) and right knee (RGT) position relative to the frontal plane – the position of each knee joint in the medial/lateral direction was described relative to a body-fixed plane created using the corresponding hip joint, ankle joint and distal foot (mid-point of medial and lateral anatomical landmarks).

To objectively define the start and end of each trial, event detection algorithms were created in Visual 3D™ by tracking the motion of the trunk, pelvis, forearms, feet and whole-body center of mass (COM). With the exception of the hose drag, hose pull and heavy drag, each task was described by two distinct phases; a descent and ascent for the lifting, squatting and lunging tasks, a "towards" and "away" from the body for the push and pull (in reference to motion of the right hand), and a "swing" and "recovery" for the chop and forced entry. The hose drag and heavy drag trials were described by three and four phases, respectively, corresponding to the stance phase of the left and right legs. Hose pull trials comprised one phase, defined as the initiation of movement to the instant at which the rope could no longer be pulled (cable reached its maximum length). Participants were instructed to pause briefly prior to and following the completion of each trial to assist with event identification. The chop and forced entry task data were processed to reflect a right handed swing (i.e. data were inverted for left handed individuals). To verify that events were defined as intended, model animations of all trials were inspected visually. Maximums and minimums were computed for each repetition. The "peak" of each variable was described as the deviation (maximum or minimum) hypothesized to be most relevant to the types of injuries sustained by firefighters (i.e. FLX – flexion, BND and TST – maximum deviation in either direction, LFT and RGT – medial displacement).

5.2.7. Statistical Analyses

Between-task comparisons (general and occupation-specific) of the maximums and minimums (of any phase) for each dependent measure were examined using a general linear model with one repeated (10 levels of task) factor (IBM SPSS Statistics, Version 20.0, Armonk, NY, U.S.A.), and when significant ($p<0.05$), post-hoc comparisons were used to investigate the differences. Sidak corrections were made to adjust for multiple comparisons. Task was found to be a significant factor in every instance tested. Each load / movement speed condition was examined separately.

To investigate whether the battery of general tasks could be used to describe each job-specific skill, the relationship (i.e. statistical difference) between each general/specific task comparison was noted. If non-significant differences were found across all dependent measures for a particular firefighting skill, it was stated that the participants' general task performance could be used to describe their execution of said skill. The deviation (maximum or minimum) hypothesized to be most relevant to the types of injuries sustained by firefighters was used to assess the relationship between tasks, which for FLX and LFT/RGT referred to the maximum spine flexion and frontal plane knee motion, respectively. Given the asymmetrical nature of the general task evaluation, the largest deviation observed (maximum or minimum) was used in all task comparisons of BND and TST. All non-significant differences are reported ($p>0.05$).

Normalized Comparisons

As a secondary analysis to facilitate comparisons between variables, each dependent measure (maximum and minimum) was normalized to the range observed across all general tasks. Briefly, the maximums and minimums for the lift, squat, lunge, push and pull were identified and used to compute a general task range (highest max – lowest min) and midpoint (average of highest max and lowest min). This midpoint was then subtracted from each of the maximums and minimums of the firefighting tasks and the result was expressed with respect to half of the computed range. In this way, the maximums and minimums observed for the general tasks were bounded by scores of -1 and 1. Normalized scores outside of this range implied that the general task performance was unable to capture the magnitude of deviation observed during the firefighting skill in question. Given that participants performed the lunge, push and pull with the right side only, symmetry was assumed when describing the maximums and minimums for each of these general tasks. This ensured that the normalized range for BND, TST, LFT and RGT was not underestimated simply because of the asymmetrical nature of the evaluation. Normalized comparisons were made on the group's data and that of each participant.

5.3. RESULTS

5.3.1. Task Comparisons

The highest p-values found for the task comparisons made between any of the general tasks and each firefighting skill are illustrated in Figure 5.3. The FLX adopted during the lift was similar to that of the chop (p=1.00), while the observed LFT and RGT were not significantly different that of the forced entry, hose drag and hose pull (also true for the squat). The RGT for the lunge was similar (p>0.05) to the hose drag and heavy drag tasks; however, it should be noted that the lunge was only tested on the right side. Had symmetry been assumed for this analysis, similar results may have been found for LFT. Similarities were also seen between the lunge and forced entry, hose drag and heavy drag for FLX, but interestingly, the relationship was found to be speed dependent. The low speed lunge conditions were comparable to the forced entry (p>0.49), while only those performed at high speed showed non-significant differences when compared to the hose drag (p=1.00) and heavy drag (p>0.62). Similarities (p=1.00) were also noted between pushing and pulling and each of the firefighting tasks, albeit most notably for BND and TST. In several instances the relationship also appeared to be speed dependent. Generally, non-significant differences (p>0.05) were noted between the general and firefighting tasks for each of the variables investigated; however, the peak deviations observed during the performance of each job-specific skill could not be described by the same combination of general patterns.

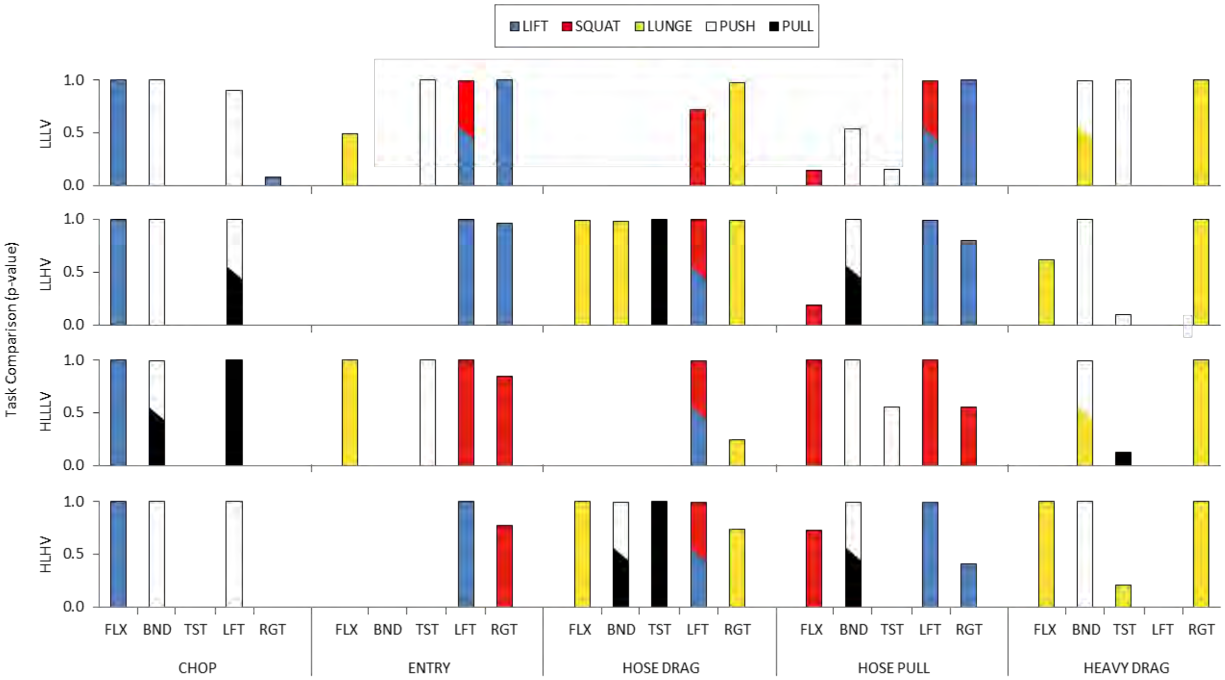


Figure 5.2. The statistical summary for task comparisons made with each condition (LLLV – low load, low velocity; LLHV – low load, high velocity; HLLV – high load, low velocity; HLHV – high load, high velocity). The data presented highlight the highest p-value found for the comparisons made in the *peak* between any of the general tasks and the corresponding firefighting skill. Instances marked by two colours imply that the same p-value was noted for two tasks. No data implies that the firefighting task was significantly different ($p<0.05$) than each of the general patterns.

5.3.2. Normalized Comparisons

In most instances, the group's general task performance was able to capture the maximum and minimum spine and frontal plane knee motion used to execute each firefighting skill (Figure 5.4). The FLX adopted to perform each firefighting task fell within the normalized range (i.e. -1 and 1), irrespective of the load and movement speed used for comparisons. Interestingly, similar findings were noted for TST, despite the rotational nature of the chop and forced entry tasks. The general tasks were also able to estimate the magnitude of LFT and RGT observed in every instance with the exception of two cases for each variable; minimum chop and heavy drag for LFT (↑ medial deviation), and minimum hose drag (↑ lateral deviation) and maximum heavy drag for RGT. Not surprisingly, the normalized boundaries were least able to capture the magnitude of BND (6 of 10 instances for LLLV); however, increasing the load and movement speed with which the general tasks were performed did appear to widen the boundaries. During the HLHV condition only the minimum hose drag and maximum forced entry were not contained.

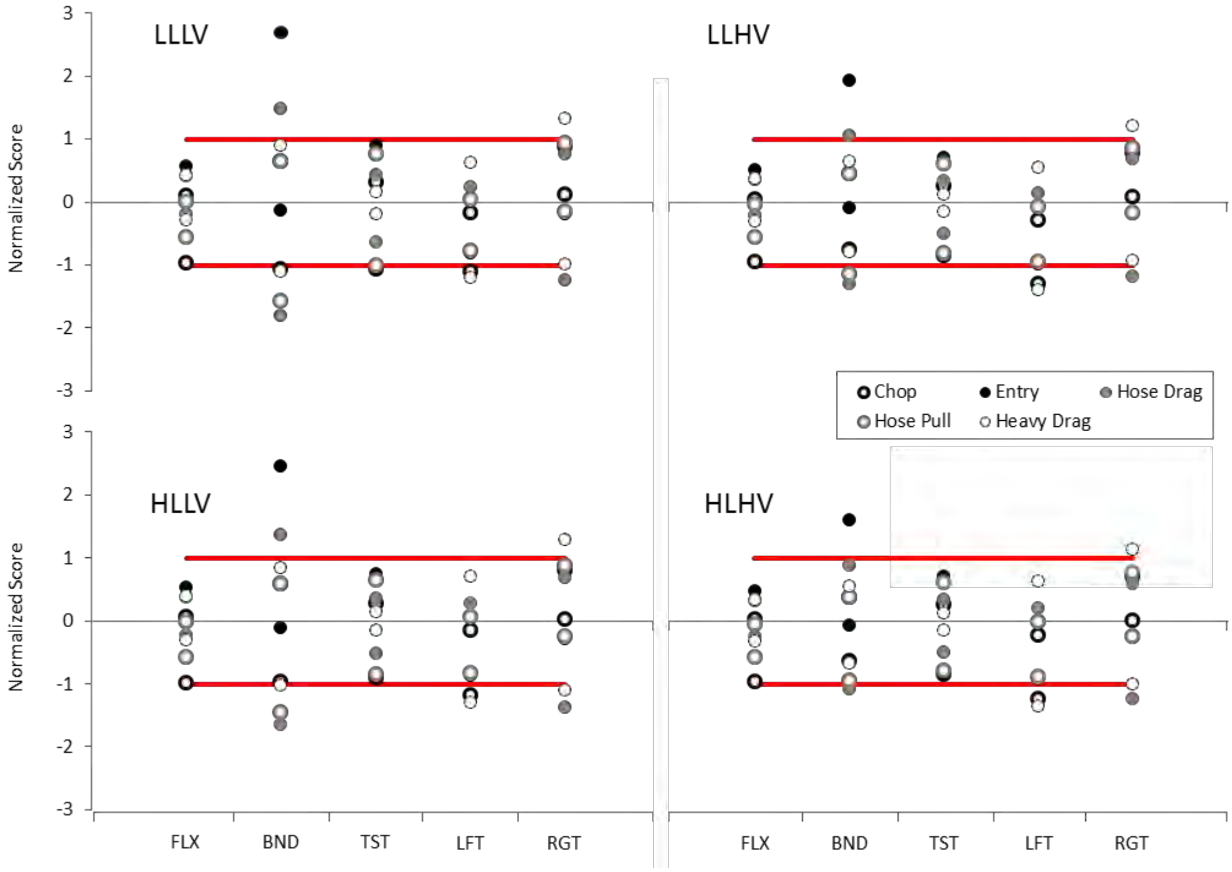


Figure 5.3. Normalized maximums and minimums for each firefighting task. Symmetry was assumed for the lunge, push and pull. The solid red lines at -1 and 1 represent the maximums and minimums observed for the general tasks. Scores outside of this range imply that the group's general task performance was unable to capture the magnitude of deviation observed during the firefighting task in question. Each of the load/movement speed conditions are presented; LLLV – low load, low velocity; LLHV – low load, high velocity; HLLV – high load, low velocity; HLHV – high load, high velocity. (FLX – spine flexion/extension; BND – spine lateral bend; TST – spine twist; LFT – left knee position; and RGT – right knee position).

Similar findings were observed when each subject's data was investigated separately (Figure 5.5); however, the group's response did not reflect that of every individual. With the exception of the heavy drag TST noted during the HLHV condition, at least one participant was found to exhibit a maximum or minimum FLX, BND, TST, LFT and RGT while performing the firefighting tasks that exceeded the general limits. Expressed as a percentage of the total number of participant scores (maximums and minimums) across all firefighting tasks, FLX was found to fall outside of the normalized boundaries with the lowest frequency (5.6% across all load/movement speed conditions), followed by TST (12.8%), RGT (23.3%), LFT (26.0%) and BND (26.0%) (Figure 5.5). It is also important to note that the general tasks' load and movement speed did influence the frequency with which the maximum and minimum deviation was captured within the generalized range; across all tasks and variables only 14.6% of the participants' scores fell outside during the HLHV condition, in comparison to 17.5%, 20.3% and 22.7% for the LLHV, HLLV, and LLLV conditions, respectively.

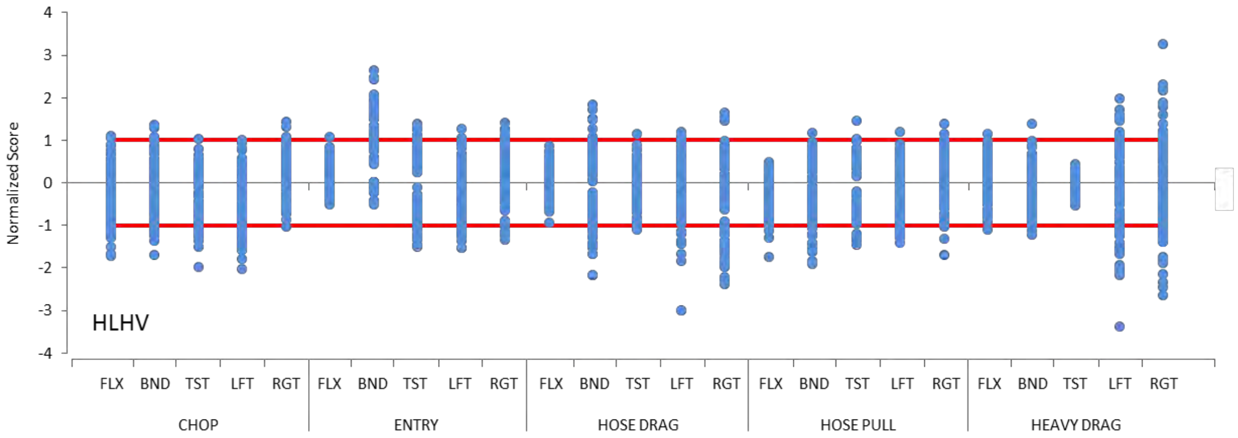


Figure 5.4. Normalized maximums and minimums for each participant. Symmetry was assumed for the lunge, push and pull. The solid red lines at -1 and 1 represent the subject-specific maximums and minimums observed for the general tasks. Scores outside of this range imply that the individual's general task performance was unable to capture the magnitude of deviation observed during the firefighting task in question. Data for the high load, high velocity (HLHV) condition is presented. (FLX – spine flexion/extension; BND – spine lateral bend; TST – spine twist; LFT – left knee position; and RGT – right knee position).

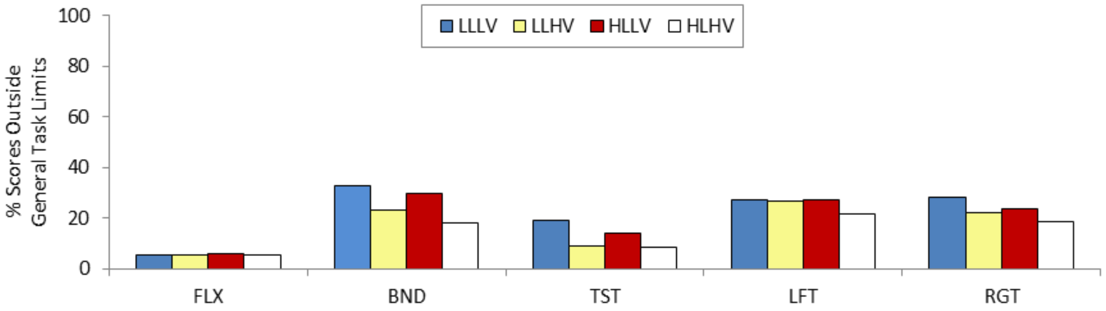


Figure 5.5. The percentage of normalized maximums and minimums across all firefighting tasks that fell beyond the limits established by the general patterns. A result of 100% would imply that in every instance possible (e.g. maximum spine flexion/extension during the hose drag) the general tasks *underestimated* the magnitude of deviation observed (i.e. high degree of specificity). Data for each of the load/movement speed conditions are presented; LLLV – low load, low velocity; LLHV – low load, high velocity; HLLV – high load, low velocity; HLHV – high load, high velocity. (FLX – spine flexion/extension; BND – spine lateral bend; TST – spine twist; LFT – left knee position; and RGT – right knee position).

5.4. DISCUSSION

Task specificity implies that an individual's performance on one task cannot be used to describe their execution of another (Baker et al., 1994). Instinctively, the notion is quite logical. Many factors can influence the way we move (e.g. perception of risk, awareness, strength), and thus a range of physiological, mechanical and behavioural adaptations could, theoretically, be exhibited in response to subtle task differences. Simply altering the load, modality or instructions, for example, might elicit a different movement strategy than was used to perform the original activity, thereby limiting the utility of generalizations. This may explain why weak relationships have been reported between exercises that at first glance appear kinematically similar (e.g. squat and vertical jump) (Baker, 1996, Baker et al., 1994, Blazevich et al., 2002, Carlock et al., 2004, Cotterman et al., 2005). It is also the reason why it was surprising, and contrary to our original hypothesis, to find that the general tasks evaluated in this study could be used to estimate the range of spine and frontal plane knee motion adopted while performing the battery of complex firefighting-specific skills. These results suggest that there may be attributes, or "key features", of an individual's movement behaviour that can be used to generalize their movement competency across a range of activities.

Over the past ten years, tremendous progress has been made towards the prediction of anterior cruciate ligament (ACL) injuries. Researchers have contrasted the movement patterns employed during non-contact ACL injury events to ACL loading mechanisms (Hewett et al., 2005) and devised evidence-based strategies to alter individuals' movement behaviour and attenuate joint loading (Hewett et al., 1996, Onate et al., 2005). In light of their successes, general whole-body movement evaluations, or pre-participation screens, have been adopted by several scientists and practitioners as a means to reveal undesirable personal movement qualities (e.g. limited joint mobility and asymmetries) (Cook et al., 2006a, Cook et al., 2006b, Mottram and Comerford, 2008), establish the risk of *any* non-contact musculoskeletal injury or complaint (Kiesel et al., 2007, Plisky et al., 2006), and assist in making recommendations for training (Hewett et al., 1999, Kiesel et al., 2011). Critical observations are described so that individuals' movement patterns can be objectively categorized/ranked as "good" or "bad", although quite often there is little evidence linking the criteria being used for these purposes to the types of injuries most commonly sustained by the population being tested. Secondly, and perhaps a more intriguing aspect of the "general screen", is that unique criteria are sometimes used to describe each screening task (Cook et al., 2006a, Cook et al., 2006b, Mottram and Comerford, 2008). When every pattern being tested is categorized with different observations (a characteristic of task specificity), it becomes exceedingly difficult to generalize the screen's findings to a different set of tasks that might be more relevant to the individual's life demands. It is interesting to note that although many experts cite task specificity as being critical to ensure the transfer of training (Bartlett et al., 2007), many successful ACL injury prediction/prevention strategies have focused on select key features of movement (e.g. frontal plane knee motion), irrespective of the activity or exercise being performed (Greska et al., 2012, Mandelbaum et al., 2005, Myer et al., 2012, Myers and Hawkins, 2010, Noyes et al., 2012). In other words, they have used a general strategy to establish the risk of injury.

The notion of generality was also supported by the findings of this study, though not in the sense that each or all of the general tasks could be used to describe the complex, whole-body movement strategies employed to perform each firefighting skill. Rather, the results highlight the fact that there may be select descriptors of motion, or key features of an individual's performance that provide insight into the movement patterns employed to execute a variety of other tasks or activities. Consider the (dis)similarities between a lifting task and an overhead chop. An individual's lifting strategy would appear dramatically different than that used to perform the chop if comparisons were made between the tasks' whole-body movement strategies. Alternatively, if specific key features (e.g. spine flexion) of both patterns were emphasized, it is possible that the two tasks could actually appear quite similar; in this study, the p-value for the lift-chop task comparison of spine flexion was 1.0 for each load/speed condition, meaning that no task difference were noted. Participants' lifting pattern also showed similarities to the forced entry, hose drag and hose pull tasks with regards to frontal plane knee motion (p-value=1.0). In fact, each of the general tasks investigated showed similarities to one or more of the occupation-specific skills. Because the unpredictable, unconstrained nature of firefighting makes it difficult to identify and evaluate all job-tasks that are relevant to the incidence of injury, the screening of general tasks using key features may provide an opportunity to assess a firefighter's relative risk of injury without having to simulate a potentially injurious event. Excitingly, this approach to movement screening may also provide a simple framework with which to make recommendations for training (Chapter 6).

Lower back, knee and shoulder injuries are commonly sustained by firefighters (Karter Jr, 2012, Poplin et al., 2012), which implies that movement patterns such as spine and frontal plane knee motion may lend insight into an individual's risk of future problems. Obviously it would be difficult to simulate the demands (musculoskeletal or cardiovascular) of every firefighting skill with general patterns such as lifting, lunging or pushing, but perhaps it is not necessary. Simply knowing if and how much spine flexion might be exhibited, for example, may be sufficient to devise an appropriate strategy to improve an individual's abilities, awareness and understanding (i.e. capacity) so that they are able to adapt their movement behaviour in a manner that is perceived as being positive. Both the group and subject-specific analyses in this study showed that with the exception of spine lateral bend during the forced entry, the magnitude of spine and frontal plane knee motion observed for the battery of general patterns exceeded that exhibited by participants while they performed the simulated firefighting tasks; select key features of the lift, squat, lunge, push and pull patterns could be used to describe the kinematics of unrelated tasks. Individual differences were seen given the range of movement strategies employed, but surprisingly, few participants demonstrated greater spine and frontal plane motion while performing the more complex tasks designed to simulate the elevated demands of firefighting.

Evaluating an individual's ability to run is probably best accomplished by having them run. There are physiological, mechanical and behavioural adaptations specific to the act of running (or whichever activity is being performed) that may not be captured with an alternative activity (e.g. cycling). However, because all endurance events impose similar general demands on the cardiovascular system (Reilly et al., 2009), there are also specific attributes or key features of an individual's ability (e.g. VO_2 max) that can be evaluated with a variety of tests. Theoretically, the evaluation of movement could be viewed in the same way. Assessing an individual's capacity (i.e. ability, awareness, understanding) to perform a particular skill (e.g. forced entry) would require that that said skill be evaluated, but their general movement behaviour, including the risk of sustaining a non-contact musculoskeletal injury, could be assessed using a battery of general tasks such as those included in this investigation. Individuals could then be categorized based on the magnitude of "uncontrolled" motion exhibited and their general tendency to adapt their movement patterns in response to an elevated demand. As was hypothesized, increasing the load and speed with which the general tasks were performed did cause participants to exhibit more spine and frontal plane motion. This highlights the fact that if administering a general screen, tasks of higher demand will provide a more conservative estimate of the deviation that might be observed while performing an unrelated activity. The finding may also indicate that limiting a movement-based evaluation to low-demand activities could skew the interpretation of any results and lead to inappropriate recommendations for training, particularly given that an individual's abilities and perception of risk will impact their movement patterns. Injuries are only influenced in part by an individual's movement patterns, but in many instances (e.g. fire suppression) it is the only factor that can be modified to attenuate the applied tissue load, maintain loading tolerance, and thus reduce the risk of injury.

The general tasks (i.e. lift, squat, lunge, push and pull) included in this investigation were chosen to reflect five commonly performed whole-body movement patterns. It was not known how each would compare to the firefighting skills being examined, but there were expectations regarding the magnitude of spine and frontal plane knee motion that would be seen. The patterns chosen were administered in such a way that they would impose a range of demands, thus eliciting a range of movement strategies amongst participants. For example, the mechanics of lifting and squatting were expected to expose spine flexion/extension and frontal plane knee motion patterns that would not be observed while pushing and pulling. On the other hand, the pushes and pulls were performed unilaterally and with a staggered stance so that the firefighters' control of spine lateral bend and twist could be observed. Had a bilateral pattern been used, participants' capacity to resist these joint motions would not have been challenged, making it difficult to approximate the deviation that was adopted while performing the battery of more demanding, job-specific tasks. It is important to note that there was not one general pattern that was better able to predict participants' ability to control each of the joint motions investigated, or one that was more closely related to a particular key feature of the five firefighting skills. Together however, the five general tasks were able to approximate the maximum deviation observed while participants performed the simulated patterns. Therefore, if using a general screen to reveal undesirable personal movement qualities, establish the risk of musculoskeletal injury, or assist in making recommendations for training, it is recommended that the screening tasks chosen be characterized by key features and of a variety such that their demands are able to expose the movement patterns or joint motions of interest.

5.5. CONCLUSIONS

An individual's movement patterns are influenced by a number of factors including their perception of risk, awareness and coordination, which lends support to the notion of task specificity – an individual's performance on one task cannot be used to describe their execution of another. However, when the execution of a task is characterized by select key features and not a gross movement strategy, two seemingly different patterns can describe similar aspects of an individual's movement behaviour. In this study, the firefighters' general task performances captured the maximum spine and frontal plane knee motion exhibited while performing the firefighting skills in 85.4% of all instances tested (high load, high velocity condition). This implies that the findings of a movement pattern evaluation, or pre-participation screen, could be generalized to estimate the risk of injury or make recommendations for training, provided that the screening tasks are chosen and administered in such a way that they challenge participants' capacity to control the motions of interest.

Chapter 6

INVESTIGATION FOUR

PERIODIZED EXERCISE AND THE TRANSFER OF TRAINING: CAN WE CHANGE THE WAY AN INDIVIDUAL MOVES?

6.1. INTRODUCTION

Periodized exercise programs and well-designed feedback protocols work – they can (and should) be used to improve capacity. Whether targeting fitness (e.g. strength) on a particular test or the movement patterns employed to perform a specific task, most interventions are able to elicit changes in the direction hypothesized by the researchers to be of benefit. For example, scientists have been able to reduce the knee abduction moment in females performing a drop jump (Myer et al., 2007, Myer et al., 2006), alleviate patellofemoral pain in runners (Noehren et al., 2011), lower spinal moments during lifting (Kernozek et al., 2006) and improve performance in weightlifting exercises such as the clean (Rucci and Tomporowski, 2010) and snatch (Winchester et al., 2009). Interestingly however, fitness-oriented interventions that do not include any movement-based instruction or feedback may have limited transfer. Recent evidence suggests that improving strength (Herman et al., 2008, McGinn, 2004) or joint range of motion (Moreside, 2010, Yuktasir and Kaya, 2009) in isolation has minimal influence on the way individuals move while performing whole-body tasks not employed in the training program. Even more intriguing (or concerning, depending on your perspective), is the possibility that changes in a movement strategy, when they do take place, might be task-specific. Noehren et al. (2011) used real-time kinematic feedback (eight sessions) to reduce hip adduction and contralateral pelvic drop while running, but found that there were no significant changes to a “transfer task” (i.e. single leg squat) thought to reflect the movement pattern used during the first half of stance.

Exercise is a tool that we all use to enhance capacity. It can be used to make difficult tasks easier and more enjoyable, prevent musculoskeletal injuries and pain, and it can allow us to perform at levels that far exceed any expectations that we have for ourselves, especially if it influences the execution of non-exercise related tasks (Carroll et al., 2001). Not every training intervention (exercise or feedback) needs to be designed with these intentions, but when investigating the prevention of injuries or the physical preparation of occupational groups the notion of transference must be considered. Too often assumptions are made regarding the generality of an adaptation simply because the newly acquired skill/movement strategy appears to be similar to that used to perform a job-related task. Enhancing movement coordination and control (ultimately what we are trying to do) is not a simple process. The adaptations demonstrated by each individual will be influenced by their prior experience, inherent structural and functional attributes and personal objectives, not to mention the characteristics of each task being learned (Caillou et al., 2002). It is therefore important to carefully consider the design and implementation of any intervention being used to affect life-related change.

It has been suggested that to ensure movement specificity and the transfer of training, exercises be prescribed that replicate the tasks of interest (Bartlett et al., 2007). For firefighters, this would imply that various high-risk, physically demanding job-tasks be simulated in a gym setting. Although such an approach might seem logical, it is unlikely to afford the most favourable adaptations – enhancing capacity to match the demands of one’s job (life) cannot be accomplished by simply prescribing a group of specific exercises. Feedback and coaching are essential to guarantee that the movement strategies being used are safe and effective and, in some environments, may actually have a greater influence on the transfer of training than the exercise itself (Swinnen et al., 1997). However, the fireground is almost certainly not one of those settings. The physical demands are of such magnitude and variety that strength, endurance, aerobic capacity, etc., should be viewed as essential components of any training program designed to prepare firefighters. Alone, movement-based instruction and feedback protocols may improve the way that incumbents perform menial tasks, but could prove to be ineffective when the challenges are increased and further capacity is required. Herman et al. (2009) suggested that using a combination of strength training and feedback may offer the greatest opportunity for transferable adaptations, although it should be noted that the investigation was designed specifically to alter various kinematic measures associated with jump landing and the risk of anterior cruciate ligament injury. The design and implementation of training strategies for firefighters is not as straightforward; enhancing their capacity often equates to preparing for the unexpected, hence the need to develop a better appreciation for the transference of training. Certainly, general adaptations are possible and learning to perform various novel "exercises" could, theoretically, influence the execution of an unrelated or job-relevant task. However, the degree to which training transfers is probably individual-, task- and program-specific. This investigation sought to explore the adaptations (fitness and movement) exhibited by professional firefighters in response to two training methodologies, differing most notably in the attention that was given to *how* each exercise was performed. Participants movement-related adaptations were evaluated post-training with five "transfer" tasks, for which they received no formal coaching or feedback.

6.2. RESEARCH DESIGN AND METHODS

6.2.1. Experimental Overview

Professional firefighters completed a comprehensive fitness evaluation (e.g. aerobic capacity, strength and endurance) and a lab-based test, wherein a battery of general tasks (i.e. squat, lunge, push, pull and lift) were performed with varying loads and speeds. Upon completion of the two testing sessions, participants were randomly assigned to one of three intervention groups: 1) "movement-oriented fitness" training; 2) "fitness" training; or 3) control. Both training interventions comprised 12-week, periodized exercise programs designed to improve the firefighters' strength, endurance, power and cardiorespiratory efficiency, but differed with regards to the attention that was given to *how* each exercise was performed. Participants in the training groups attended three 1.5-hour sessions each week, and were coached by accredited (National Strength and Conditioning Association) strength and conditioning professionals. At no time were the objectives of the evaluations, the differences between each training group or the overall rationale of the study discussed with the firefighters. Within one week of completing the 12-week protocol, participants returned for a second fitness and lab-based testing session identical to that conducted prior the intervention. The battery of general tasks, for which no formal coaching or feedback was provided, served as "transfer" tests to evaluate the movement-related adaptations to training. Select descriptors of motion that have been previously cited as possible mechanisms of injury were used for comparative purposes.

6.2.2. Participant Selection

Seventy-five men from the Pensacola Fire Department were recruited to participate in this investigation. All men were free of musculoskeletal injury or pain at the time of testing and were on full active duty. Because of the time commitment required, 14 were unable to participate in the lab-based tests and an additional 9 individuals withdrew before completing their 12 weeks of training, leaving 52 complete pre/post training data sets. The mean (SD) age, height, body mass and Functional Movement Screen™ (FMS) score of the participants completing the pre and post fitness and lab-based testing sessions are described in Table 6.1. The FMS is a qualitative whole-body movement-based screen that has demonstrated some efficacy in the prediction of injuries (Kiesel et al., 2007) and is currently being used to help guide the design of exercise programs for athletes and firefighters (Kiesel et al., 2011, Peate et al., 2007). The FMS was used in this study strictly as a means to match the general movement competency of the three intervention groups prior to training. The University's Office of Research Ethics, the Baptist Hospital Institutional Review Board and the City of Pensacola each approved the investigation and all participants gave their informed consent before the data collection began.

Table 6.1. The mean (SD) age, height, body mass and Functional Movement Screen™ (FMS) score of participants completing the pre and post fitness (N=66) and lab-based testing (N=52) sessions. The characteristics described are of each intervention group before training.

Sample	Group (N)	Age (years)	Height (m)	Body Mass (kg)	FMS™ Score
Fitness Testing	Movement (23)	39.3 (10.5)	1.81 (0.06)	89.4 (14.2)	12.9 (2.7)
	Fitness (19)	35.1 (10.0)	1.80 (0.07)	89.9 (13.2)	12.8 (1.7)
	Control (24)	38.9 (9.4)	1.79 (0.05)	92.6 (15.6)	12.9 (2.4)
Lab Testing	Movement (21)	38.7 (10.4)	1.81 (0.06)	89.6 (14.7)	13.0 (2.8)
	Fitness (16)	35.9 (9.7)	1.80 (0.07)	91.6 (13.4)	12.4 (1.5)
	Control (15)	38.3 (9.3)	1.80 (0.06)	96.0 (15.2)	12.9 (2.9)

6.2.3. Test Selection

Fitness Evaluation

A modified version of the fitness assessment recommended by the International Association of Fire Fighters (IAFF) in their Wellness-Fitness Initiative (WFI) was used to evaluate six components of general fitness: 1) body composition – estimated using the sum of seven skin-folds (i.e. triceps, chest, mid axilla, subscapula, abdomen, supra-iliac and thigh) and the generalized equations for predicting body density and body fat percentage from Jackson and Pollock (1978); 2) aerobic capacity – assessed with the Gerkin treadmill protocol (Gerkin et al., 1997); 3) muscular strength – grip strength was measured with a hand dynamometer; 4) muscular endurance – evaluated with a combination of dynamic (i.e. maximum push-ups) and static (i.e. plank (prone and side) and Biering-Sorensen) tests; 5) lower-body power – counter-movement jump height; and 6) flexibility – assessed with the modified sit-and-reach. Additional upper- and lower-body power testing (5 loads each) was conducted using a Keiser (Keiser®, Fresno, CA, U.S.A.) chest press and squat machine, respectively.

Transfer Tasks

The lab-based transfer tasks were chosen to reflect commonly performed whole-body movement patterns. The five tasks were: 1) Lift – from standing, individuals lifted a box (0.33 x 0.33 x 0.28 m) to waist height and returned it to the ground; 2) Squat – from standing, individuals performed a bodyweight squat (depth was self-selected); 3) Lunge – from standing, individuals lunged forwards onto their right leg and returned to the starting position; 4) Push – from a staggered split stance (left leg forwards), individuals performed a standing cable press with the right arm; 5) Pull – from a staggered split stance (left leg forwards), individuals will performed a standing cable pull with the right arm.

6.2.4. Experimental Protocol

Fitness Testing

Upon arriving for the first testing session (i.e. fitness test), a registered dietician recorded the participant's height, body mass and conducted the seven-site skin-fold assessment. The fitness test was then administered by an accredited strength and conditioning professional using the following procedures: 1) aerobic capacity – participants performed a sub-maximal treadmill test while being monitored (ventilation and heart rate) with an IMETT™ System (FitStrength Inc.™, San Juan Capistrano, CA). Following three minutes at 4.8 km/h (0% grade) and one minute at 7.2 km/h (0% grade), the speed or incline was raised every minute (0.8 km/h or 2% grade) until volitional fatigue. Approximately 20 minutes of rest was given before proceeding to the next test; 2) sit-and-reach – seated on the floor with their legs extended and feet flat against the sit-and-reach box, participants were instructed to reach forwards as far as possible (hands placed on top of one another). Three trials were performed; 3) grip strength – participants were seated on a chair of standard height without armrests. The shoulder was adducted with the elbow flexed to 90° and the wrist was placed in a neutral position (Harkonen et al. 1993). A hand dynamometer (Takei Kiki Kogyo, Nigata, Japan) was used to record three maximal effort trials with each hand, in an alternating fashion; 4) upper-body power – using the Keiser® chest press machine, participants performed three explosive repetitions with five loads (13.6, 22.7, 31.8, 40.8 and 49.9 kg). Elbow position and seat height were standardized and approximately 15 s and 60 s of rest was given between each repetition and load, respectively. Power measurements were recorded from the machine's display; 5) vertical jump – counter-movement jump height was evaluated from a stationary start with a Vertec Jump Measuring Device. Reach height was estimated by the height touched when both arms were placed overhead with the fingers interlaced as the test administrator applied pressure to the elbows. Three maximal effort trials were performed; 6) max push-ups – participants were asked to perform push-ups until fatigue while maintaining a neutral spine. The test was terminated when the arms could no longer be extended or the required depth (0.10 m) was not achieved – a 0.10 m thick pad was placed beneath the body; 7) lower-body power – using the Keiser® squat machine, participants performed three explosive repetitions with five loads (18.1, 27.2, 40.8, 54.4 and 68.0 kg). The starting position was standardized at a knee angle of 90° and participants were instructed not to jump. Approximately 15 s and 60 s of rest was given between each repetition and load, respectively. Power measurements were recorded from the machine's display; 8) front plank – while lying prone with the hips and knees extended and a neutral spine, participants supported themselves on their elbows and toes for as long as possible. The test was terminated when the hip position or spine posture could no longer be maintained; 9) side plank – while side lying with the hips and knees extended, participants supported themselves on one elbow and both feet (top leg forwards) for as long as possible. The test was terminated when the straight-body position could no longer be maintained. Approximately two minutes of rest was given before testing the left side; and 10) Biering-Sorensen – with the upper-body cantilevered over the end of a bench and the hips and knees secured, participants held their body in a straight line with the arms across the chest for as long as possible. The test was terminated when the body could no longer be held in a position parallel to the floor. Approximately two minutes of rest was given between each task. With the exception of the Keiser upper- and lower-body power tests, which used the median score, the participants' best performance was used for comparative purposes.

Lab-Based Testing

The second testing session was designed to document participants' movement and coordination patterns when performing each of the general, whole-body tasks in the absence of coaching or feedback. Upon arrival, individuals were instrumented with reflective markers and familiarized with the tasks they would be asked to perform using a standard set of instructions. The initial exposure to each task reflected a low-demand scenario, whereby the external load and movement speed were low (LLLV – low load, low velocity). The lifting trials were performed with 6.8 kg, the squats and lunges were completed with bodyweight, and the push and pull loads (Keiser®, Fresno, CA, U.S.A.) were set at 4 kg (15 units on Keiser® display) and 6.5 kg (20 units), respectively. The five tasks were performed in a randomized fashion (three repetitions each) and approximately 15 s and 60 s of rest was given between each trial and task, respectively. If a participant failed to perform three repetitions correctly (e.g. they lost balance) an additional trial was performed after 15 s of rest. Once all tasks had been completed the movement speed and external load were modified in three ways: 1) low load, high velocity (LLHV) – increase in movement speed only; participants were asked to complete each trial as fast as was comfortable; 2) high load, low velocity (HLLV) – increase in external load only; the lifts were performed with 22.7 kg (NIOSH recommended maximum (Waters et al., 1993)), the squat and lunge trials were performed with an 18.2 kg weighted vest, and the push and pull loads were set at 9.8 kg (30 units) and 13.6 kg (40 units), respectively; 3) high load, high velocity (HLHV) – increase in movement speed and external load. Each condition was performed sequentially based on the expected musculoskeletal demands (i.e. LLLV → LLHV → HLLV → HLHV). Beyond the task instruction, which was standardized within and between participants, no feedback was given regarding task performance at any point throughout the investigation. Compression shorts, a tight t-shirt and athletic shoes were worn at all times.

Training

Following the completion of both baseline testing sessions, participants were assigned (stratified randomization) to one of three groups: 1) “movement-oriented fitness” training (MOV); 2) “fitness” training (FIT); or 3) control (CON), each matched for age, height, body mass and FMS score. The two interventions comprised 12-week, periodized exercise programs (MOV – 4 phases, FIT – 3 phases) designed to improve general fitness characteristics (e.g. aerobic capacity) and performance outcomes (e.g. treadmill time), but each differed with regards to the selection of exercises (MOV exercises were chosen to challenge various key movement features such as spine flexion and extension), intensities, training volumes and perhaps most notably, the attention that was given to *how* each exercise was performed (via cues based on the coach’s visual observations). This is not to say that the movement-oriented program was focused solely on “technique”, but rather that the objective was to utilize exercise, in the global sense, as means to bring attention to, enhance, and engrain desired movement coordination and control patterns (Newell, 2009), such that changes to an individual's gym-based performance might impact their safety (i.e. injury risk) and effectiveness (i.e. performance outcomes) when performing tasks outside of the gym setting. To accomplish this, The MOV program incorporated several evidence-based strategies that have been previously hypothesized or demonstrated to reduce the risk of injury (Cowling et al., 2003, Dempsey et al., 2009, Hewett et al., 1999, Knapik et al., 2004, Mandelbaum et al., 2005, McGill, 1998, Tyler et al., 2001), which could conceivably, also improve performance. All exercises and corresponding demands (e.g. frequency, intensity and time) were chosen to "perturb" the firefighters' movement system, whereby their objective throughout the 12-week program was to become increasingly robust or resilient to the perturbations as training became more demanding (i.e. the firefighters' strength, endurance, awareness, etc. to avoid uncontrolled spine and knee motion was challenged). Further, the same "key movement features" were emphasized with every exercise such that the individuals' movement patterns became the focus and mechanism to elicit transfer, in contrast to replicating specific activities pertinent to the occupation of firefighting. For example, the firefighters were made aware of the potential implications surrounding uncontrolled spine motion while executing all relevant exercises, and given cues to adapt their movement behaviour. Theoretically, a push-up could be used to elicit a behavioural change while advancing hose given that in each case the firefighter's capacity to resist an external flexor moment about the low back is being challenged. Conversely, the primary objective of the FIT program was to make the firefighters as "fit" as possible. Exercise "technique" was monitored and feedback was provided when necessary (for safety purposes), but the coach's emphasis was on maximizing performance and fitness outcomes in the gym environment. Details pertaining to each exercise program are outlined in Table 6.2 and 6.3.

Participants in both groups attended three 1.5-hour sessions each week at a local training facility and were coached by accredited strength and conditioning professionals. They were asked to refrain from performing any additional exercise for the duration of the investigation. At no time were the objectives of the evaluations, the differences between each training group or the study hypotheses discussed with the participants. The coaches were also blinded to the lab-based testing protocols (transfer tasks) and instructed to refrain from sharing their thoughts regarding the test/study objectives with their group of firefighters. Each individual was required to attend at least 30 of the 36 training sessions to be included in the analyses. Within one week of completing the training program (week 13), participants returned for a second fitness and lab-based testing session identical to that conducted prior the intervention. The CON participants were asked to maintain their current fitness regime for 12 weeks before returning to complete their fitness and lab-based post-tests.

Table 6.2. The movement-oriented fitness training (MOV) program. Specific exercises for the movements patterns described (e.g. upper body push) were chosen at the discretion of the group's coaches to best suit each firefighter. Patterns sharing a numerical descriptor (e.g. 1A and 1B) were performed in a circuit fashion. The coach assigned appropriate loads for each set x repetition. N/A implies not applicable to that phase.

	PHASE 1		PHASE 2				PHASE 3				PHASE 4	
DAY 1	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12
1A. Upper Body Push	3 x 8	3 x 8	3 x 12	3 x 12	3 x 12	3 x 12	4 x 15	4 x 15	4 x 15	4 x 15	3 x 8	3 x 8
1B. Supplemental	N/A	N/A	3 x 5	3 x 5	3 x 5	3 x 5	3 x 5	3 x 5	3 x 5	3 x 5	3 x 5	3 x 5
1C. Lower Body Pull	3 x 8	3 x 8	3 x 12	3 x 12	3 x 12	3 x 12	4 x 12	4 x 12	4 x 12	4 x 12	3 x 8	3 x 8
1D. Supplemental Rest: 45s between sets	N/A	N/A	N/A	N/A	N/A	N/A	3 x 8	3 x 8	3 x 8	3 x 8	3 x 5	3 x 5
2A. Rotation	3 x 8	3 x 8	3 x 12	3 x 12	3 x 12	3 x 12	N/A	N/A	N/A	N/A	3 x 6	3 x 6
2B. Supplemental Rest: 45s between sets	2 x 6	2 x 6	2 x 5	2 x 5	2 x 5	2 x 5	N/A	N/A	N/A	N/A	2 x 5	2 x 5
3A. Upper Body Push	3 x 8	3 x 8	3 x 12	3 x 12	3 x 12	3 x 12	3 x 12	3 x 12	3 x 12	3 x 12	2 x 9	2 x 9
3B. Lower Body Pull Rest: 45s between sets	3 x 8	3 x 8	3 x 12	3 x 12	3 x 12	3 x 12	3 x 12	3 x 12	3 x 12	3 x 12	2 x 9	2 x 9
CARDIO (run, bike, elliptical)	30 min MED INTENSITY (low, mod and high HR)		30 min MED INTENSITY (low and high HR)				30 min MED INTENSITY (low, mod and high HR)				30 min MED INTENSITY (low, mod and high HR)	
DAY 2	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12
1A. Lower Body Push	3 x 8	3 x 8	3 x 10	3 x 10	3 x 10	3 x 10	4 x 12	4 x 12	4 x 12	4 x 12	3 x 6	3 x 6
1B. Supplemental	N/A	N/A	3 x 5	3 x 5	3 x 5	3 x 5	3 x 6	3 x 6	3 x 6	3 x 6	3 x 5	3 x 5
1C. Upper Body Pull	3 x 8	3 x 8	3 x 10	3 x 10	3 x 10	3 x 10	4 x 12	4 x 12	4 x 12	4 x 12	3 x 6	3 x 6
1D. Supplemental Rest: 45s between sets	N/A	N/A	N/A	N/A	N/A	N/A	3 x 6	3 x 6	3 x 6	3 x 6	3 x 5	3 x 5
2A. Rotation	3 x 8	3 x 8	3 x 10	3 x 10	3 x 10	3 x 10	N/A	N/A	N/A	N/A	2 x 6	2 x 6
2B. Supplemental Rest: 45s between sets	2 x 6	2 x 6	2 x 8	2 x 8	2 x 8	2 x 8	N/A	N/A	N/A	N/A	2 x 6	2 x 6
3A. Lower Body Push	3 x 8	3 x 8	3 x 10	3 x 10	3 x 10	3 x 10	3 x 12	3 x 12	3 x 12	3 x 12	2 x 7	2 x 7
3B. Upper Body Pull Rest: 45s between sets	3 x 8	3 x 8	3 x 10	3 x 10	3 x 10	3 x 10	3 x 12	3 x 12	3 x 12	3 x 12	2 x 7	2 x 7
CARDIO (run, bike, elliptical)	30 min LOW INTENSITY (low and mod HR)		30 min LOW INTENSITY (low and mod HR)				30 min LOW INTENSITY (low and mod HR)				30 min LOW INTENSITY (low, mod and high HR)	
DAY 3	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12
1A. Upper/Lower Body Push	3 x 10	3 x 10	3 x 10	3 x 10	3 x 10	3 x 10	4 x 10	4 x 10	4 x 10	4 x 10	3 x 6	3 x 6
1B. Supplemental	N/A	N/A	3 x 5	3 x 5	3 x 5	3 x 5	3 x 6	3 x 6	3 x 6	3 x 6	3 x 5	3 x 5
1C. Upper/Lower Body Pull	3 x 10	3 x 10	3 x 8	3 x 8	3 x 8	3 x 8	4 x 10	4 x 10	4 x 10	4 x 10	3 x 6	3 x 6
1D. Supplemental Rest: 45s between sets	N/A	N/A	3 x 5	3 x 5	3 x 5	3 x 5	3 x 6	3 x 6	3 x 6	3 x 6	3 x 5	3 x 5
2A. Rotation	3 x 10	3 x 10	3 x 8	3 x 8	3 x 8	3 x 8	N/A	N/A	N/A	N/A	3 x 6	3 x 6
2B. Supplemental Rest: 45s between sets	2 x 6	2 x 6	2 x 5	2 x 5	2 x 5	2 x 5	N/A	N/A	N/A	N/A	2 x 8	2 x 8
3A. Lower Body Push	3 x 8	3 x 8	3 x 8	3 x 8	3 x 8	3 x 8	3 x 12	3 x 12	3 x 12	3 x 12	2 x 7	2 x 7
3B. Upper Body Pull Rest: 45s between sets	3 x 8	3 x 8	3 x 8	3 x 8	3 x 8	3 x 8	3 x 12	3 x 12	3 x 12	3 x 12	2 x 7	2 x 7
CARDIO (run, bike, elliptical)	30 min HIGH INTENSITY (low, mod and high HR)		30 min HIGH INTENSITY (low and high HR)				30 min HIGH INTENSITY (low, mod and high HR)				30 min HIGH INTENSITY (low and high HR)	

Table 6.3. The fitness training (FIT) program. Specific exercises for the movements patterns described (e.g. upper body push) were chosen at the discretion of the group's coaches to best suit each firefighter. Patterns sharing a numerical descriptor (e.g. 1A and 1B) were performed in a circuit fashion. The coach assigned appropriate loads for each set x repetition. N/A implies not applicable to that phase.

	PHASE 1				PHASE 2				PHASE 3			
DAY 1	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12
1A. Trap Bar Deadlift	3 x 8	3 x 8	3 x 8	2 x 5	3 x 6	3 x 6	3 x 6	2 x 4	4 x 6	4 x 6	4 x 6	2 x 4
1B. Lat Pull-down/Pull-Up	3 x 8	3 x 8	3 x 8	2 x 5	3 x 6	3 x 6	3 x 6	2 x 4	4 x 6	4 x 6	4 x 6	2 x 4
1C. Bench Press Rest:60s between sets	3 x 8	3 x 8	3 x 8	2 x 5	3 x 6	3 x 6	3 x 6	2 x 4	4 x 6	4 x 6	4 x 6	2 x 4
2A. Dumbbell Military Press	2 x 10	2 x 10	2 x 10	1 x 6	3 x 10	3 x 10	3 x 10	2 x 6	3 x 8	3 x 8	3 x 8	2 x 5
2B. Dumbbell Bent Over Row	2 x 10	2 x 10	2 x 10	1 x 6	3 x 10	3 x 10	3 x 10	2 x 6	3 x 8	3 x 8	3 x 8	2 x 5
2C. Single Leg Squat Rest:30s between sets	2 x 10	2 x 10	2 x 10	1 x 6	3 x 10	3 x 10	3 x 10	2 x 6	3 x 8	3 x 8	3 x 8	2 x 5
3A. Leg Extension	2 x 15	2 x 15	2 x 15	1 x 15	2 x 10	2 x 10	2 x 10	1 x 10	2 x 8	2 x 8	2 x 8	1 x 8
3B. Hamstring Curl	2 x 15	2 x 15	2 x 15	1 x 15	2 x 10	2 x 10	2 x 10	1 x 10	2 x 8	2 x 8	2 x 8	1 x 8
3C. Abdominal Curl-Up Rest:30s between sets	2 x 15	2 x 15	2 x 15	1 x 15	2 x 10	2 x 10	2 x 10	1 x 10	2 x 8	2 x 8	2 x 8	1 x 8
CARDIO (run, bike, versa)	30 min LOW INTENSITY				30 min LOW INTENSITY				30 min LOW INTENSITY			
DAY 2	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12
1A. Squat Press	2 x 15	2 x 15	2 x 20	1 x 12	2 x 25	2 x 25	2 x 30	1 x 20	2 x 35	2 x 35	2 x 40	1 x 25
1B. Horizontal Pull-Up	2 x 15	2 x 15	2 x 20	1 x 12	2 x 25	2 x 25	2 x 30	1 x 20	2 x 35	2 x 35	2 x 40	1 x 25
1C. Medicine Ball Slam Rest: 45s between sets	2 x 15	2 x 15	2 x 20	1 x 12	2 x 25	2 x 25	2 x 30	1 x 20	2 x 35	2 x 35	2 x 40	1 x 25
2A. Push-Up	2 x 15	2 x 15	2 x 20	1 x 12	2 x 25	2 x 25	2 x 30	1 x 20	2 x 35	2 x 35	2 x 40	1 x 25
2B. Lunge Walk	2 x 15	2 x 15	2 x 20	1 x 12	2 x 25	2 x 25	2 x 30	1 x 20	2 x 35	2 x 35	2 x 40	1 x 25
2C. Medicine Ball Rotation Rest: 45s between sets	2 x 15	2 x 15	2 x 20	1 x 12	2 x 25	2 x 25	2 x 30	1 x 20	2 x 35	2 x 35	2 x 40	1 x 25
3A. Grip (Squeeze)	2 x 15	2 x 15	2 x 20	1 x 20	2 x 25	2 x 25	2 x 30	1 x 20	2 x 35	2 x 35	2 x 40	1 x 25
3B. Wrist Roll	2 x 15	2 x 15	2 x 20	1 x 20	2 x 25	2 x 25	2 x 30	1 x 20	2 x 35	2 x 35	2 x 40	1 x 25
3C. Exercise Ball Crunch Rest: 45s between sets	2 x 15	2 x 15	2 x 20	1 x 20	2 x 25	2 x 25	2 x 30	1 x 20	2 x 35	2 x 35	2 x 40	1 x 25
CARDIO (run, bike, versa)	30 min MED INTENSITY (work:rest – 6:1 to 1:1)				30 min MED INTENSITY (work:rest – 6:1 to 1:1)				30 min MED INTENSITY (work:rest – 6:1 to 1:1)			
DAY 3	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12
1A. Seated Leg Press	2 x 30s	2 x 30s	2 x 30s	1 x 30s	3 x 30s	3 x 30s	3 x 30s	2 x 30s	3 x 45s	3 x 45s	3 x 45s	2 x 30s
1B. Seated Chest Press	2 x 30s	2 x 30s	2 x 30s	1 x 30s	3 x 30s	3 x 30s	3 x 30s	2 x 30s	3 x 45s	3 x 45s	3 x 45s	2 x 30s
1C. Cable Row Rest:45s between sets	2 x 30s	2 x 30s	2 x 30s	1 x 30s	3 x 30s	3 x 30s	3 x 30s	2 x 30s	3 x 45s	3 x 45s	3 x 45s	2 x 30s
2A. Machine Squat	2 x 30s	2 x 30s	2 x 30s	1 x 30s	2 x 45s	2 x 45s	2 x 45s	1 x 45s	2 x 45s	2 x 45s	2 x 45s	1 x 45s
2B. Machine Shoulder Press	2 x 30s	2 x 30s	2 x 30s	1 x 30s	2 x 45s	2 x 45s	2 x 45s	1 x 45s	2 x 45s	2 x 45s	2 x 45s	1 x 45s
2C. V-Pulls Rest:45s between sets	2 x 30s	2 x 30s	2 x 30s	1 x 30s	2 x 45s	2 x 45s	2 x 45s	1 x 45s	2 x 45s	2 x 45s	2 x 45s	1 x 45s
3A. Biceps Curl	2 x 30s	2 x 30s	2 x 30s	1 x 30s	2 x 45s	2 x 45s	2 x 45s	1 x 45s	2 x 60s	2 x 60s	2 x 60s	1 x 60s
3B. Triceps Extension	2 x 30s	2 x 30s	2 x 30s	1 x 30s	2 x 45s	2 x 45s	2 x 45s	1 x 45s	2 x 60s	2 x 60s	2 x 60s	1 x 60s
3C. Side Plank Rest:45s between sets	2 x 30s	2 x 30s	2 x 30s	1 x 30s	2 x 45s	2 x 45s	2 x 45s	1 x 45s	2 x 60s	2 x 60s	2 x 60s	1 x 60s
CARDIO (run, bike, versa)	30 min HIGH INTENSITY (work:rest – 1:1 to 1:6)				30 min HIGH INTENSITY (work:rest – 1:1 to 1:6)				30 min HIGH INTENSITY (work:rest – 1:1 to 1:6)			

6.2.5. Data Collection and Signal Processing

During the lab-based test, three-dimensional motion data were measured using a passive motion capture system (Vicon, Centennial, CO, U.S.A.). Reflective markers were placed on 23 anatomical landmarks to assist in defining the proximal and distal endpoints of the trunk, pelvis, thighs, shanks and feet, although the hip joint centers and knee joint axes were also determined "functionally" using similar methods to those described by Begon et al. (2007) and Schwartz and Rozumalski (2005). Briefly, participants were asked to perform 10 repetitions of "hula-hooping" (closed-chain hip circumduction) and standing open-chain knee flexion/extension for the hip and knee joint computations, respectively. Visual 3D™ software (Version 4, C-Motion, Inc., Germantown, MD, U.S.A.) was used to calculate the axis of rotation between every pair of measured adjacent segment configurations. The most likely intersection and orientation of the axes was used to define the effective joint centers and joint axes, respectively. Using functionally defined segment endpoints for the shank and thigh has been shown to minimize the variation introduced via bony palpation (or digitization) and thus provide a more stable way to create the link segment model (Frost et al., 2012c). Sets of 4 and 5 markers, fixed to rigid pieces of plastic, were secured to each segment with Velcro® straps and used to track the position and orientation of each body segment in 3D space throughout the collection. However, each thigh segment was tracked with the pelvis and corresponding shank to minimize the influence of soft tissue motion artifact (Frost et al., 2012b). One static calibration trial (standing) was collected such that the orientation of each segment's local axis system, as defined by the anatomical markers or segment endpoints, could be determined via a transformation from an axis system embedded within each rigid body. The anatomical markers were removed once the calibration procedures were completed. The marker data was collected at 160 Hz, padded with one second of data (Howarth and Callaghan, 2009) using an end-point reflection method (Smith, 1989) and smoothed with a low-pass filter (4th order, dual pass Butterworth) with a cut-off frequency of 6 Hz (Winter, 2005).

6.2.6. Data Analyses

The movement patterns used to perform the transfer tasks were characterized with five variables, each chosen to reflect a coaching observation that has been previously cited as a possible mechanism for injury (e.g. spine motion (Callaghan and McGill, 2001, Lindsay and Horton, 2002, Marshall and McGill, 2010) and frontal plane knee motion (Chaudhari and Andriacchi, 2006, Hewett et al., 2005, Hewett et al., 2009)). The five variables were: 1-3) spine flexion/extension (FLX), lateral bend (BND) and axial twist (TST) - the relative orientation of the trunk was expressed with respect to the pelvis (Woltring, 1991) and the corresponding direction cosine matrix was decomposed with an Euler rotation sequence of flexion/extension, abduction/adduction and axial rotation (Cole et al., 1993) to compute the spine angle about each axis. The orientation of the lumbar spine in a relaxed upright standing trial was defined as zero degrees; and 4-5) left (LFT) and right knee (RGT) position relative to the frontal plane – the position of each knee joint in the medial/lateral direction was described relative to a body-fixed plane created using the corresponding hip joint, ankle joint and distal foot (mid-point of medial and lateral anatomical landmarks).

To objectively define the start, mid-point and end of each trial, event detection algorithms were created in Visual 3D™ by tracking the motion of the trunk, pelvis, right forearm (push and pull) and whole-body center of mass (COM). Each task was separated into two phases; a descent and ascent for the lifting, squatting and lunging tasks, and a “towards” and “away” from the body for the push and pull (in reference to motion of the right hand). To verify that events were defined as intended, model animations of all trials were inspected visually. Maximums, minimums and means were computed for the five dependent variables (each phase separately) and the data series were normalized to twenty samples so that time-series comparisons could be made. The “peak” of each variable was described as the deviation (maximum, minimum or range) hypothesized to be most relevant to the types of injuries sustained by firefighters (i.e. FLX – flexion, BND and TST – range, LFT and RGT – medial displacement).

6.2.7. Statistical Analyses

The fitness-related adaptations to training were evaluated using a general linear model with one between- (3 levels of group – MOV, FIT and CON) and one within-subject (2 levels of time – pre and post training) factor (IBM SPSS Statistics, Version 20.0, Armonk, NY, U.S.A.). Tukey post-hoc comparisons were used to investigate the differences and all significant interactions ($p<0.05$).

Participants' movement adaptations to each transfer task were evaluated using the empirically documented biological variability between- and within-subjects. The following two measurements were used to describe the magnitude of each pre-post change: 1) an effect size (ES) – the pre-post differences in FLX, BND, TST, LFT and RGT were expressed as a function of the pooled between-subject variation (a score of one implied that the pre-post difference was equal to the variation observed between participants). A positive effect implied that less motion (deviation) was observed post-training; and 2) a within-subject normalized difference (WND) – the pre-post differences were normalized by the maximum variation observed within participants (± 1SD of the group mean) for any metric (i.e. max, min or mean) or condition of that particular variable. This approach was also used to examine the subject-specific responses for each dependent measure. A score greater than one or less than negative one implied that the individual's adaptation to training was greater than the average variability observed within participants (± 1SD), and thus defined herein as a biologically significant or "meaningful" change (Chapter 3). Using the *maximum* within-subject variation observed for any metric provided a more conservative estimate of the boundary conditions with which a "meaningful" difference was defined, in comparison to the method outlined in Chapter 3. Each load/movement speed condition was investigated separately.

6.3. RESULTS

6.3.1. Fitness Adaptations

Post-training, the MOV group showed significant improvements in every aspect of fitness that was tested (i.e. body composition, aerobic capacity, muscular strength and endurance, power and flexibility). With the exception of the left and right side plank and the two lightest upper-body power tests, improvements ($p<0.05$) were noted on each of the tests administered (Table 6.4 and Table 6.5). Similar training adaptations were seen amongst participants in the FIT group; every aspect of their fitness improved dramatically ($p<0.05$), with the exception of their flexibility, as was measured by performance on the sit-and-reach test. The CON participants showed significant improvements on 3 of the 21 tests (left grip, max push-ups and 18.1 kg lower body power); however, in each case the magnitude of change was smaller than that observed for either of the training groups.

Table 6.4. Training adaptations for measures of general fitness as outlined in the International Association of Fire Fighters' Wellness-Fitness Initiative. Data represent the magnitude of change post-training. The * denotes a significant change ($p<0.05$) post-training.

GROUP	BOD (%)	TRD (s)	LPK (s)	RPK (s)	FPK (s)	EXT (s)	LGP (kg)	RGP (kg)	PSH (reps)	CMJ (cm)	SIT (cm)
Movement	-1.4*	62.4*	9.1	-5.5	47.5*	35.1*	2.0*	2.0*	13.8*	2.6*	4.4*
Fitness	-1.3*	88.6*	21.2*	11.1	63.7*	50.8*	1.9*	1.3	25.6*	2.6*	-0.3
Control	0.2	-22.6	-10.8	-4.0	5.6	-5.9	1.7*	1.4	4.5*	0.4	-1.5

BOD – body composition; TRD – treadmill; LPK – left plank; RPK – right plank; FPK – front plank; EXT – Biering Sorensen; LGP – left grip; RGP – right grip; PSH – max pushups; CMJ – vertical jump ; SIT – sit-and-reach

Table 6.5. Training adaptations for upper- and lower-body power. Data represent the magnitude of change post-training. The * denotes a significant change ($p<0.05$) post-training.

GROUP	Upper Body Power (W)					Lower Body Power (W)				
	13.6 kg	22.7 kg	31.8 kg	40.8 kg	49.9 kg	18.1 kg	27.2 kg	40.8 kg	54.4 kg	68.0 kg
Movement	14.3	14.7	33.7*	41.4*	46.0*	51.3*	66.0*	78.8*	124.2*	124.8*
Fitness	40.5*	8.8	12.2	31.9*	41.2*	101.2*	98.4*	129.7*	166.7*	176.8*
Control	14.8	6.0	0.5	5.7	-4.2	31.7*	29.7	15.3	29.4	17.7

6.3.2. Movement Adaptations

The post-training adaptations to each transfer task are described herein by the peak deviation observed for each dependent measure; however, similar responses were noted for the means of each variable across tasks and conditions (Appendix D). The magnitude of change described as a "meaningful" adaptation for each variable and task is described in Appendix D.

Lifting

The most substantial post-training lifting-specific adaptations were exhibited by the MOV group (Figure 6.1). Participants showed marked improvements (less motion) in FLX for each of the load/movement speed conditions during the descent and ascent phase (WND > 0.5; ES > 0.3 for three of four conditions). A similar trend was noted for LFT and

RGT, but there were only four (of 16) conditions wherein the ES was greater than 0.2, and each had a WND less than 0.5. The FIT intervention however, did not elicit any changes to the variables that were used to characterize the lifting pattern. The WND of each post-training difference was less than 0.25, and there was only one instance with an ES greater than 0.2 (LFT during the ascent phase of LLLV condition); it was also negative. In comparison, the CON group exhibited five changes with a WND greater than 0.25, although they too, with the exception of one RGT adaptation, described an increase in motion post-training (negative change).

Squatting

Participants' post-training adaptations to squatting were dramatically different than those observed while lifting, despite the visual similarities between the two tasks. The MOV group showed marked improvements in LFT and RGT (less medial deviation) for each load/movement speed condition during the descent and ascent phase of the squat, though only those observed on the right side had a WND and ES greater than 0.3 (Figure 6.2). Interestingly, the largest post-training differences (WND > 0.6; ES > 0.5) were seen when participants' were exposed to the highest demands (i.e. HLHV). A negative change was noted in FLX during the LLLV condition (WND > 0.4; ES > 0.2); however, similar adaptations were not found with any other load/movement speed combination. Perhaps most notable for the squat task were the post-training changes in FLX amongst the FIT participants; substantially more motion was observed across conditions during both phases of the movement (WND > 0.9; ES > 0.4). Similar responses were seen in LFT and RGT, although the magnitudes of change were much smaller and not consistent across all conditions. The participants in the CON group did not appear to adapt their movement behaviour post-training.

Lunging

Several post-training adaptations were observed amongst firefighters in all three groups; however, like the two previously discussed transfer tasks, the MOV participants exhibited the most substantial positive change (Figure 6.3); improvements were noted in FLX, BND and TST across all conditions for both phases of the movement, albeit to varying degrees. The adaptations to BND were of a larger magnitude during the descent (WND > 0.3; ES > 0.5), and interestingly, the post-training differences in FLX and TST appeared to be speed-dependent; greater adaptations were seen during the high speed conditions (WND > 0.3; ES > 0.2 for FLX and WND > 0.5; ES > 0.9 for TST during the ascent). With the exception of a positive change in RGT during the ascent phase of the LLLV condition (WND = 0.32; ES = 0.31), no post-training differences were observed in the frontal plane knee motion of the MOV group.

As was seen amongst firefighters in the MOV group, the FIT participants showed an improved ability to resist BND and TST post-training. The BND adaptations were also larger during the descent phase (WND > 0.2; ES > 0.2) and a speed-dependent response was seen in TST (WND > 0.5; ES > 0.9 for ascent). However, unlike the MOV group, FIT participants performed the lunge with more FLX and RGT (negative adaptation) post-training. Only one of the load/movement speed conditions prompted a change in FLX wherein the WND and ES were greater than 0.4 and 0.2, respectively (i.e. LLHV), but all four were marked by substantial changes in RGT (WND > 0.3; ES > 0.3). Notable changes in FLX, BND and TST were also seen amongst participants in the CON group; however, in each case, the post-training adaptation was directed towards an increase in motion (negative response), and opposite to that exhibited by the MOV group.

Pushing

Once again, the most notable post-training adaptations were demonstrated by the MOV participants (Figure 6.4); changes exceeding a WND of 1.4 and an ES of 0.8 were seen in BND and TST. With the exception of a modest increase in LFT (negative response) during the ascent phase of the LLLV and HLHV conditions (WND > 0.3; ES > 0.3), the MOV intervention appeared to have little influence on FLX and LFT. With regards to the FIT intervention, the post-training adaptations were similar to those observed for the lunge. Substantial improvements were seen in BND and TST, albeit most notably during the "away" phase (WND > 0.3; ES > 0.2 for BND and WND > 0.9; ES > 0.5 for TST), and participants exhibited a negative adaptation (more motion) to FLX and frontal plane knee motion. A positive change in FLX was noted for the LLLV condition (WND > 0.4; ES > 0.2); however, when the load and movement speed were modified, thereby increasing the task's demands, negative changes exceeding a WND of 0.9 and an ES of 0.3 were observed. Post-training, the FIT participants exhibited an increase in LFT across all conditions, although the adaptation was more prominent during the "towards" phase (WND > 0.3; ES > 0.3). The CON group did not display any consistent post-training changes to any of the descriptors of motion being investigated.

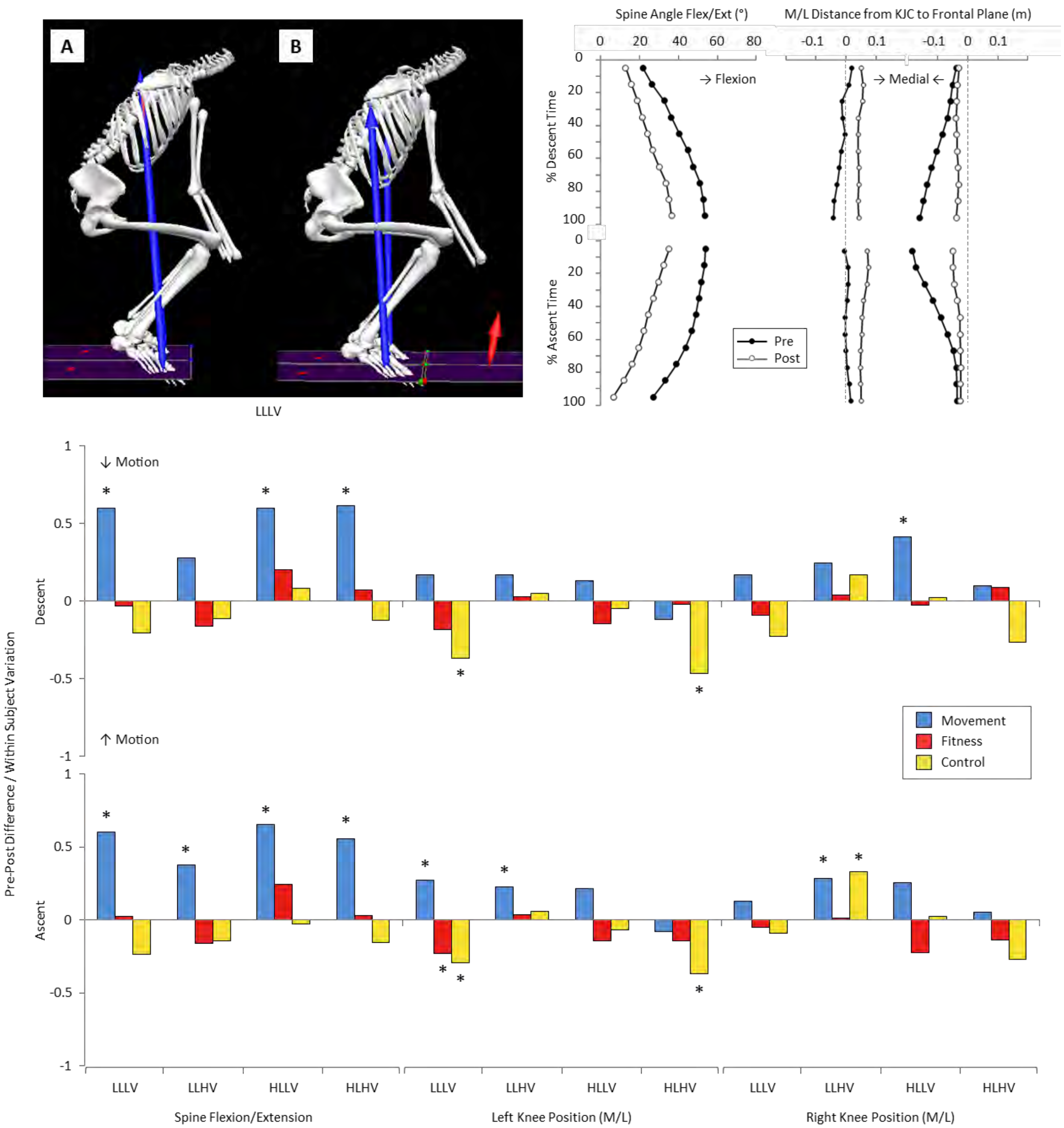


Figure 6.1. Lifting-related training adaptations in the peak spine and knee motion for each condition (load x speed) and group. Changes are presented as a function of the maximum within-subject variation + 1SD observed for a given variable (i.e. that of the max, min or mean of either phase for any load or speed) for the descent (top) and ascent (bottom) phase of each lift. The effect size (ES) of each difference is also described by the inclusion of one (ES=0.2-0.4), two (0.4-0.6) or three (>0.6) asterisks. A positive change reflects less motion post-training. The model animation and time-series data (LLLV) highlight the pre-post changes (A to B) in spine and frontal plane knee motion observed for one participant from the *MOV* group.

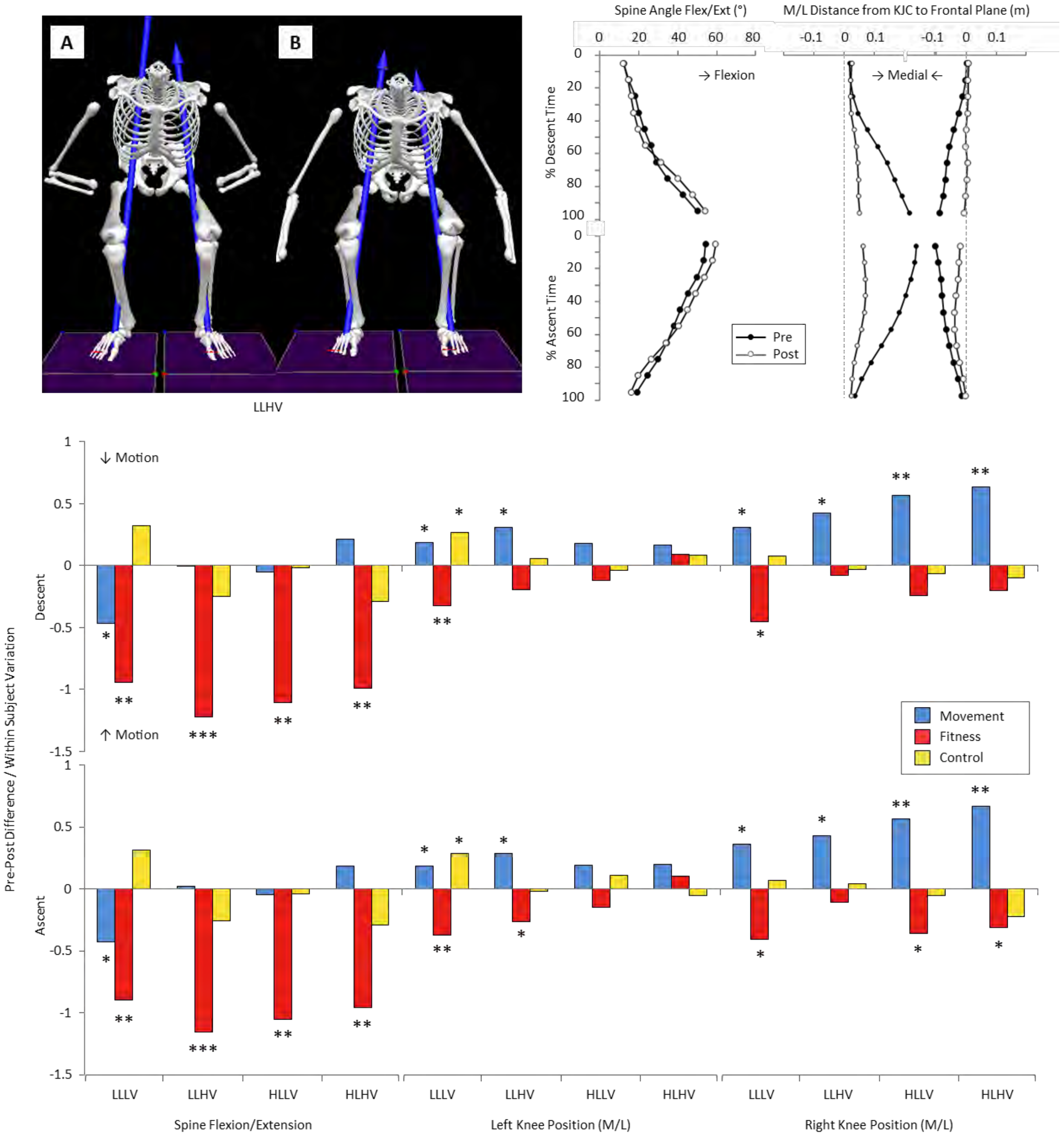


Figure 6.2. Squatting-related training adaptations in the peak spine and knee motion for each condition (load x speed) and group. Changes are presented as a function of the maximum within-subject variation + 1SD observed for a given variable (i.e. that of the max, min or mean of either phase for any load or speed) for the descent (top) and ascent (bottom) phase of each squat. The effect size (ES) of each difference is also described by the inclusion of one (ES=0.2-0.4), two (0.4-0.6) or three (>0.6) asterisks. A positive change reflects less motion post-training. The model animation and time-series data (LLHV) highlight the pre-post changes (A to B) in spine and frontal plane knee motion observed for one participant from the *MOV* group.

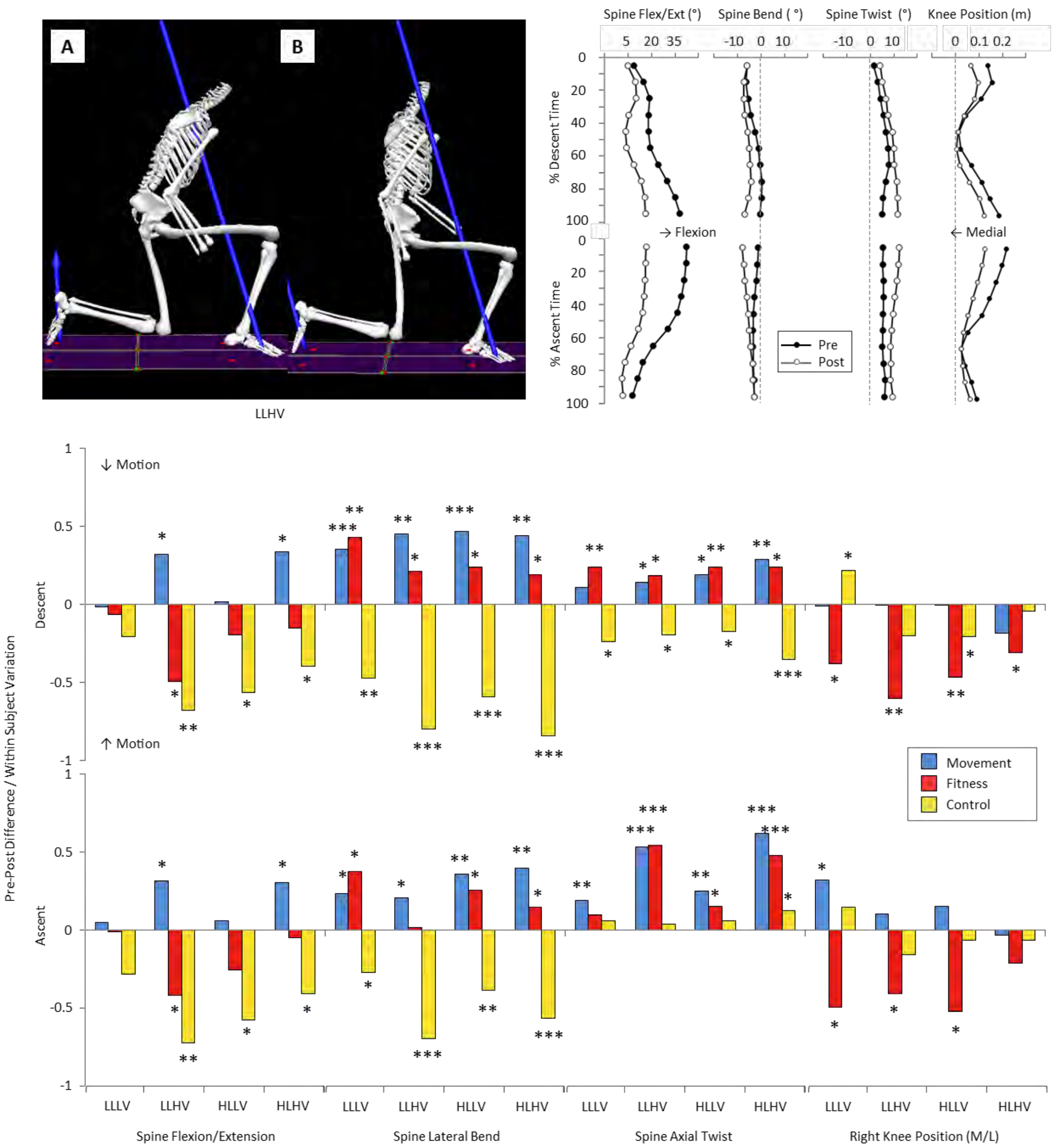


Figure 6.3. Lunging-related training adaptations in the peak spine and knee motion for each condition (load x speed) and group. Changes are presented as a function of the maximum within-subject variation + 1SD observed for a given variable (i.e. that of the max, min, range or mean of either phase for any load or speed) for the descent (top) and ascent (bottom) phase of each lunge. The (ES) effect size of each difference is also described by the inclusion of one (ES=0.2-0.4), two (0.4-0.6) or three (>0.6) asterisks. A positive change reflects less motion post-training. The model animation and time-series data (LLHV) highlight the pre-post changes (A to B) in spine and frontal plane knee motion for one participant from the *MOV* group (LLHV).

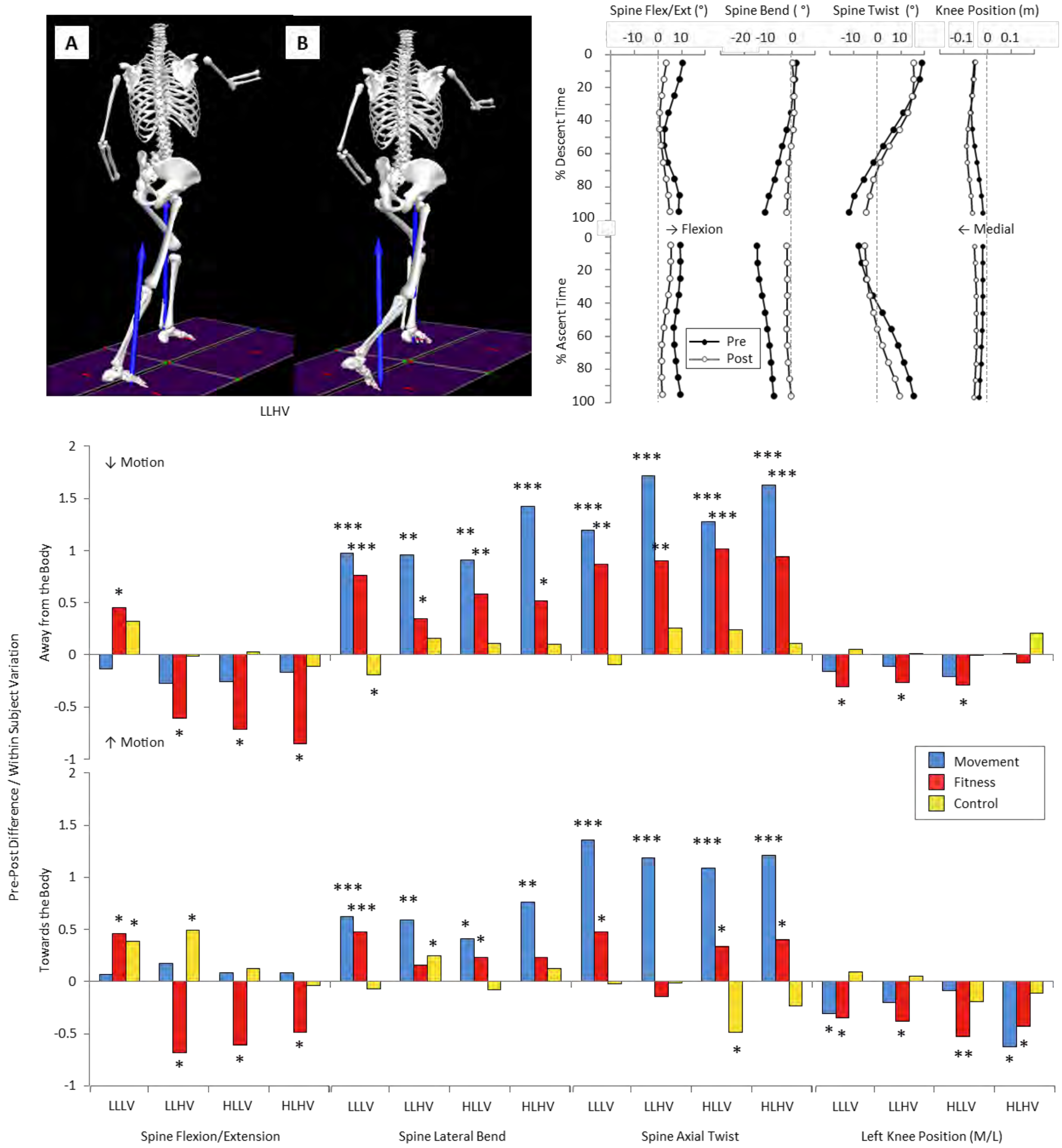


Figure 6.4. Pushing-related training adaptations in the peak spine and knee motion for each condition (load x speed) and group. Changes are presented as a function of the maximum within-subject variation + 1SD observed for a given variable (i.e. that of the max, min, range or mean of either phase for any load or speed) for the two phases of each push. The effect size (ES) of each difference is also described by the inclusion of one (ES=0.2-0.4), two (0.4-0.6) or three (>0.6) asterisks. A positive change reflects less motion post-training. The model animation and time-series data (LLHV) highlight the pre-post changes (A to B) in spine and frontal plane knee motion observed for one participant from the *MOV* group (LLHV).

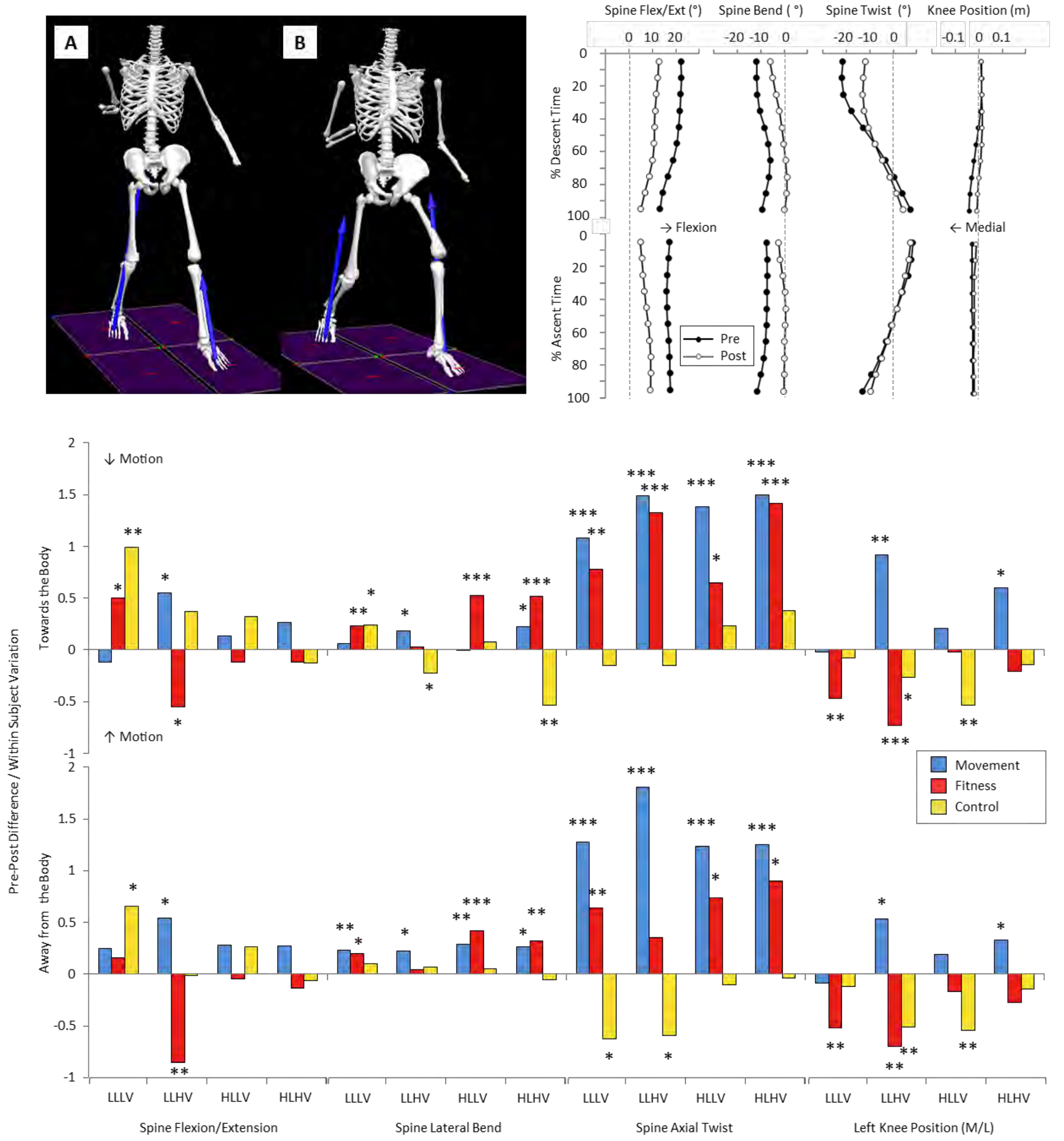


Figure 6.5. Pulling-related training adaptations in the peak spine and knee motion for each condition (load x speed) and group. Changes are presented as a function of the maximum within-subject variation + 1SD observed for a given variable (i.e. that of the max, min, range or mean of either phase for any load or speed) for the two phases of each pull. The effect size (ES) of each difference is also described by the inclusion of one (ES=0.2-0.4), two (0.4-0.6) or three (>0.6) asterisks. A positive change reflects less motion post-training. The model animation and time-series data (LLHV) highlight the pre-post changes (A to B) in spine and frontal plane knee motion observed for one participant from the *MOV* group (LLHV).

Pulling

The largest positive adaptations for the pulling task were seen in TST for both intervention groups (Figure 6.5); however, the MOV participants also demonstrated improvements in FLX, BND and LFT. Post-training, the MOV group exhibited similar changes to TST in response to all load/movement speed conditions for both phases of the movement; each improvement was characterized by a WND and ES greater than 1.1 and 0.6, respectively. The post-training adaptations to FLX and BND were also positive, but, the magnitude of change was not consistent across conditions. With regards to LFT, the MOV intervention appeared to have had a speed-dependent effect as the largest post-training differences were noted for the LLHV and HLHV conditions (WND > 0.3; ES > 0.2).

The FIT intervention was also able to elicit substantial improvements in TST, the most notable of which were seen during the “towards” phase. Interestingly, during this portion of the movement, the speed at which the pull was executed may have also influenced the post-training response, given that the largest changes were seen when the pull was performed quickly (WND > 1.3; ES > 0.6). Marked improvements in BND were also observed during the two heavy conditions (WND > 0.3; ES > 0.4); however, as was found with the squat, lunge and push, in several instances the FIT participants performed with substantially more FLX and LFT (negative response) post-training. For example, the observed change in FLX during the “away” phase of the LLHV condition was characterized by a WND and ES of 0.85 and 0.40, respectively. The post-training changes in LFT do appear to be light load-specific, but they too describe an increase in motion (WND > 0.5; ES > 0.4). With the exception of a positive FLX response to the LLLV condition (WND > 0.6; ES > 0.3) all substantial post-training adaptations exhibited by the CON group were negative.

6.3.3. Subject-Specific Adaptations

More firefighters who participated in the MOV intervention exhibited “meaningful” changes in FLX, BND, TST, LFT and RGT for each transfer task, in comparison to individuals from either of the two other groups (Figure 6.6), with the exception of one instance; BND during the first phase of the pull. Expressed as a percentage of the total number of subjects in the group, 43% of all MOV participants (averaged across variables and tasks) exhibited *only* positive "meaningful" changes post-training during the first phase of each task. This is in comparison to 30% and 23% for the FIT and CON participants, respectively. Similar within-subject adaptations were seen during the second phase of each task; 38%, 30% and 29% of participants from the MOV, FIT and CON, respectively, showed positive "meaningful" changes post-training.

When considering the negative "meaningful" adaptations to training, the findings were reversed; the MOV group had the fewest number of participants exhibiting more motion (negative response) post-training (Figure 6.6). Expressed as percentage of the total number of participants, 19% of the MOV participants showed *only* negative "meaningful" responses to training, in comparison to 26% and 36% from the FIT and CON groups, respectively. Results for the second phase of each task were again quite similar; 21%, 28% and 32%, of participants from the MOV, FIT and CON groups, respectively, adapted their movement behaviour and used more motion post-training to execute each of the transfer tasks.

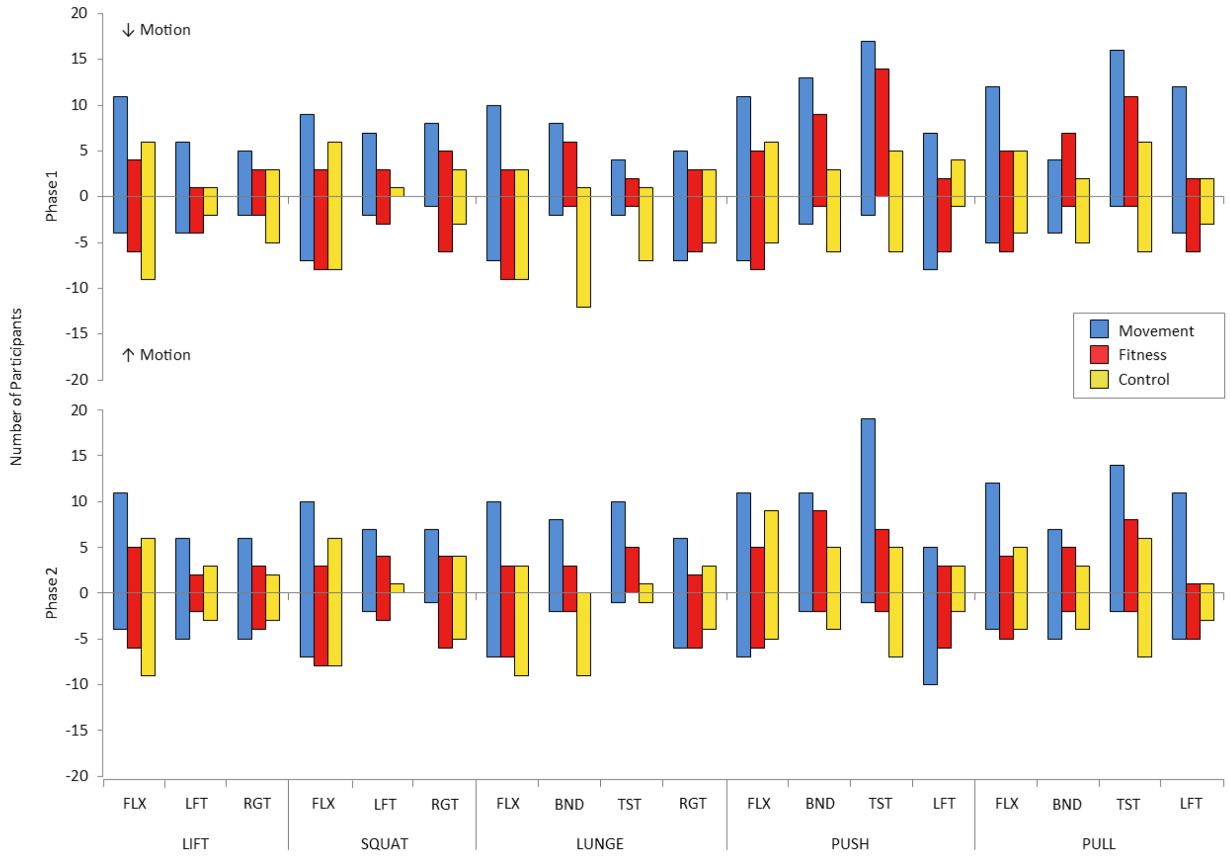


Figure 6.6. The number of participants exhibiting pre-post differences greater than the maximum within-subject variation +1SD (i.e. "meaningful" difference) in the lumbar spine and frontal plane knee motion observed during each task. Only those participants who demonstrated similar directional changes across all load x speed conditions were counted. The differences presented reflect changes to the peaks (or ranges for spine lateral bend and twist) of each variable; however, similar trends were observed for the means. A positive change reflects less motion post-training.

6.4. DISCUSSION

Exercise is a tool that can be used to enhance our capacity. It can be used to make difficult tasks easier and more enjoyable, prevent musculoskeletal injuries and pain, and it can allow an individual to perform at levels that far exceed any prior aspirations. However, the findings of this investigation lend support to the notion that the degree to which training transfers may be individual-, activity- and intervention-specific. The firefighters participating in both exercise programs showed substantial changes in every aspect of fitness tested; body composition, aerobic capacity, muscular strength and endurance, and upper- and lower-body power all improved post-training, but interestingly, only the movement-oriented fitness group exhibited positive movement-related adaptations to each transfer task. More specifically, this group of firefighters adapted their movement behaviour and used less spine and frontal plane knee motion post-training while performing five whole-body tasks of varying demands that were not explicitly coached during the 12-week intervention. The fitness-trained firefighters did show select improvements in these same measures, although they also exhibited a tendency, whether in spite of or because of their elevated fitness, to employ movement strategies comprising more uncontrolled motion (e.g. increase in spine flexion); a critical observation that may suggest that the physical preparation of firefighters, or any other high-risk occupational group, cannot be achieved by emphasizing fitness alone.

Being physical fit, in the traditional sense, may help to protect against future injury (Cady et al., 1979, Jones et al., 1993a, Knapik et al., 2001), but prior to devising an intervention it may be important to ask *why* a firefighter with superior strength or endurance, for example, might be better prepared. Similarly, there might be value in first asking *how* improving one's flexibility could assist with the prevention of non-contact musculoskeletal injuries. Hilyer et al. (1990) found that improving the overall flexibility in a cohort of firefighters (six-month intervention) did not reduce the incidence of injury in the two years following the investigation. Likewise, "plyometric" and "core strengthening" programs, created to improve various components of fitness, have been unable to reduce the incidence of anterior cruciate ligament injury (Pfeiffer et al., 2006) and back pain (Nadler et al., 2002), respectively. Perhaps being physically "fit" does not equate to being physically prepared for one's job. Fitness is essential, particularly for firefighters, but alone it is likely not sufficient to ensure peak performance and long-term durability; it simply reflects an individual's potential. For example, poor torso extensor endurance (a traditional measure of fitness) has been cited as a marker for future low back troubles in men (Beiring-Sorensen, 1984), although it is not one of the commonly described mechanisms of low back injury (e.g. spine posture (Callaghan and McGill, 2001)). A possible explanation is that superior endurance provides the opportunity to adopt spine-sparing postures or movement patterns for extended periods of time by delaying the onset of fatigue. But, if individuals cannot (or choose not to) adopt these patterns for any number of reasons, muscular endurance becomes secondary and will have little bearing on the risk of injury. A firefighter's job is and always will be physically demanding so there is an inherent risk to the occupation that cannot be avoided, but unfortunately many of the injuries incurred are the direct result of incumbents' efforts to improve their fitness. A recent study conducted in collaboration with the Tucson Fire Department found that one third of all injuries sustained between 2004 and 2009 resulted from exercise-related activities, while patient handling, training drills and fireground operations accounted for just 17%, 11% and 10%, respectively (Poplin et al., 2012). Great fitness in the presence of poor mechanics (movement) or great mechanics in the presence of poor fitness will limit performance and increase one's chances of sustaining a musculoskeletal injury. Both scenarios reflect the undesirable state where an individual's demands may exceed their capacity.

With the above in mind, traditional fitness measures such as strength, endurance and aerobic capacity might be best considered in light of how they impact the movement system. The movement system is made-up of skeletal and ligamentous structures that provide levers and motion restraints, neuromuscular components that control skeletal motion, and cardiorespiratory elements that supply metabolic energy (aerobic/anaerobic), slow the fatigue process, and regulate body temperature during motion. If any one of these components is functioning poorly (i.e. a specific fitness measure is low), performance and injury potential are affected. Therefore, firefighters must be sufficiently *fit to move* in a safe and effective manner. Consider the firefighter with excellent joint range of motion, great body awareness, but poor muscular strength. He/she may have the capacity to perform safely and effectively when the task's demands are low (e.g. minimal strength or anaerobic capacity is required), but might become injured while at the scene of a fire when in a more demanding environment. Faced with the elevated physical demands of fire suppression, this individual lacks the muscular strength and cardiorespiratory efficiency needed to preserve sound mechanics (demands > capacity). A similar outcome would be expected for the firefighter who has focused his/her efforts on improving muscular strength. He/she might lack the flexibility, endurance or awareness necessary to move in a manner that promotes safe and effective firefighting, and thus may need to emphasize another aspect of fitness or become more aware to improve their performance and avoid future injury. Particularly given the evidence to suggest that improving strength (Herman et al., 2008, McGinn, 2004) or joint range of motion (Moreside, 2010, Yuktasir and Kaya, 2009) in isolation has minimal influence on the way individuals move while performing whole-body tasks.

This is precisely how the movement-oriented fitness program was designed. Strength, endurance and aerobic capacity were deemed essential components of each training phase (i.e. non-linear periodization), but they were not progressed by sacrificing *how* the firefighters performed a particular activity. That is not to say that participants were given "corrective" exercises or taught how to activate a specific muscle in hopes of eliciting adaptations that would transfer to more complex dynamic tasks (both of which are strategies that have been used previously to try and alter an individual's movement patterns (e.g. Lubahn et al., 2011)). A firefighter's job can be unpredictable, high-risk and extremely demanding, so they were trained like athletes using fundamental principles of exercise science. They were challenged and given an opportunity to improve all aspects of fitness, but did so in an environment whereby their movement patterns were used as a guide to progress the demands (e.g. load) of each exercise. The program was designed to elevate the demands at which each firefighter could move safely and effectively, via changes to their fitness, awareness or understanding of injury and performance (i.e. capacity). Although it was not possible to evaluate the degree to which each participant improved given the methodological design of the study, there was evidence to support an increase in capacity amongst the movement-trained firefighters. Positive movement-related adaptations were noted across all load/speed conditions for each transfer task, and in select instances (e.g. spine flexion during the lunge) changes were only noted during the high speed trials that imposed the greatest demands.

To say that a training program "emphasizes movement" can be interpreted in many ways, particularly without a common framework with which to describe a movement pattern as "good" or "bad". It is also very easy to become overwhelmed with the nuances of a specific exercise or the inherent variability observed between people, which if not recognized, could skew the interpretation of any observations and misdirect the recommendations being made to improve an individual's safety or effectiveness. To address this issue and establish a foundation from which to build on in future work, the movement program's coach focused his attention on "key features" of each exercise, including several critical observations that have been linked to the prevention of musculoskeletal injury (e.g. neutral frontal plane alignment of the lower extremity ((Hewett et al., 2005)). This type of approach, whereby exercise is used to target the motion patterns that drive elevated joint loading has been hypothesized as one of the most effective strategies to protect against future anterior cruciate ligament injury (Myer et al., 2012). Placing an emphasis on select "key features" does not imply that there is an "optimal" way to move under all conditions; there is not. It simply highlights the fact that fundamental principles of biomechanics can (and should) be used to provide insight as to why a particular pattern could be described as "good" and "bad". Remarkably, these same "key features" were found to differentiate the post-training adaptations of the two intervention groups, across all transfer tasks.

The principle of specificity suggests that to become more proficient at a particular skill, be it a job task, exercise or movement pattern, you must repeatedly perform that specific skill (Bartlett et al., 2007). However, this implies that "practice makes perfect", when instead, perhaps it simply "…makes permanent". Without the capacity to perform safely or effectively, the rehearsal of a task does not guarantee that one's performance on that task will improve, and unfortunately if uncontrolled motion is noted, it is quite possible that the repeated exposure to a particular demand would eventually lead to injury (e.g. overuse injury). For example, Almeida et al. (Almeida et al., 1999) followed 1296 marine recruits prospectively through 12 weeks of training and found that of the 40% to become injured (which in itself is an issue), 78% were diagnosed with an overuse injury. Given the unpredictable and chaotic environments inherent to firefighting, it would not be possible for incumbents to rehearse every job-task that may place undue stress on the body, nor may it be the most appropriate way to influence the transfer of training. Instead, perhaps specificity should be viewed in relation to the complexity of the environment such that further variation is introduced, to the loads, speeds, movement patterns, etc., as the training program progresses and becomes more "specific", or relevant to the demands of an individual's life. Conceivably, this would provide an opportunity for individuals to develop the capacity (i.e. ability, understanding, awareness) to perform a variety of tasks described by similar "key features", thereby improving their ability to control motion in a changing environment and potentially the transfer of training (Newell, 2009). Although the results of this study are limited to the battery of general patterns tested, the movement-trained participants did exhibit less spine and frontal plane knee motion post-training across all transfer tasks, and despite the impact that the external load and speed of movement can have on our movement behaviour (Chapter 4), in most cases similar adaptations were noted across all load/speed conditions.

The results of this investigation lend support to the notion that exercise can be used to change the way an individual moves; however, the key word might be "*individual"*. Every participant was different and responded to training in a way that was unique to their abilities, awareness and understanding. More movement-trained firefighters did exhibit positive "meaningful" changes post-training (fewer also exhibited negative changes), in comparison to the fitness intervention, but each group's adaptations did not reflect those of *all* its participants. For example, every firefighter participating in the fitness-training program did not adopt more spine flexion during the squat tasks post-training (as was seen for the group). It must also be acknowledged that each participant did not perform in the exact same manner before they were exposed to the exercise intervention. Some firefighters exhibited little uncontrolled motion when first performing each of the transfer tasks and may therefore have shown minimal positive change (if any) despite the fact that their movement patterns would be perceived as "good", while others may have adapted in a positive way but would still be considered "bad". Given the possibility that many participants had never considered the way they moved while exercising, it is also conceivable that a select few became focused on a single aspect of their movement behaviour, thereby neglected one or more of the other "key features". Consider the individual who "lifts with their legs and not their back", but in reality is a "toe-squatter" with discomfort in their knees. Fundamental principles of mechanics tell us that it would be beneficial to provide this individual with guidance to utilize their hips more effectively by “sitting back”, thereby reducing the knee loading demands. But, in doing so they may demonstrate an increase in spine flexion (initially anyways) as they become more familiar with the adapted pattern. That said, if our training recommendations were based solely on the group’s behaviour, we may have failed to recognize this individual as a “toe squatter” in the first place. As a scientific community we must acknowledge the fact that in many instances the mean response does not reflect that of each participant so that we can devise the most appropriate strategies to investigate the evaluation of movement and the transfer of training.

6.5. CONCLUSION

A well-designed exercise program can be used to change an individual’s habitual movement patterns, which for occupational athletes such as firefighters, soldiers and police officers, implies that training can have a direct impact on their safety and effectiveness; however, and emphasis must be placed on *how* the participants move. Emphasizing fitness characteristics (e.g. aerobic capacity) and performance outcomes (e.g. maximum push-ups) alone may not be the most effective strategy to elevate one’s level of physical preparedness. Despite showing tremendous improvements in every aspect of fitness tested, the fitness-trained firefighters may have increased their risk of future injury following the twelve weeks of training given a propensity to adopt more spine and frontal plane knee motion while performing each of the transfer tasks. These findings were in contrast to those seen amongst the movement-trained participants whereby less uncontrolled motion was adopted across each load/speed condition.

The degree to which training transfers, and thus the effectiveness of an intervention, will likely be individual-, task-, and program (coaches included)-specific. However, the fact that a group of firefighters, with little knowledge or appreciation for how they move, exhibited more control and coordination post-training is extremely promising with regards to the prevention of future musculoskeletal injury, and could assist in the establishment of a framework to physically prepare any occupational group.

Chapter 7

SUMMARY AND CONCLUSIONS

Every individual lives with a unique set of physical demands that stem from tasks they need or want to perform. For firefighters, these demands reflect the skills necessary to safely fight a live fire or effectively assist at the scene of an accident, but they also encompass the activities that are performed at the end of the day – going for a run, doing chores around the house or playing with their kids. To perform each of these activities safely and effectively, every firefighter must be sufficiently *fit to move* in a manner such that their capacity meets/exceeds their demands. As such, one of the most critical factors in predicting who will and will not become injured might be an individual's movement patterns. This thesis comprised four studies, each of which explored fundamental questions pertaining to the description and evaluation of individuals' movement behaviour and the transfer of exercise. The knowledge gained provides scientists and practitioners with novel insights into movement variability, single-subject analyses, movement screening, coaching, exercise prescription and program design. However, at a more global level, this work assists in the establishment of a worker-centered framework that can be used to guide future injury prevention research and the physical preparation of occupational groups such as firefighters.

Movement patterns are inherently variable. For any number of reasons each of us will never perform a given task in the exact same way, we will not respond in the same manner to changing a task's demands, nor will we exhibit similar adaptations to a general intervention. Therefore, whether attempting to prevent injury, enhance performance or improve one's quality of life, any physical preparation program should be designed to accommodate the heterogeneity of its participants (e.g. age, anthropometrics, previous experiences, etc.); consideration must be given to the individual. When constrained by the group's "average" behaviour, there is greater opportunity to skew the interpretation of any findings and overlook several important and potentially novel insights regarding the movement-related adaptations that are exhibited in response to the particular stimulus, demand, or exercise being investigated. It was for this reason that the first study of this thesis examined the utility of using participants' within-subject variation to establish boundary criteria outside of which kinematic changes could be described as biologically significant, or "meaningful". Although considerable between- and within-subject variation was noted in each of the dependent measures chosen to characterize firefighters' movement patterns (between was higher for each variable and task), the proposed method could successfully define change limits, based on explicit criteria, when just two trials were included in the analyses. Collecting several trials should always be considered as best practice, particularly given that the inclusion of additional repetitions did provide a more stable estimate of the mean and a better representation of the dispersion, but in many experimental designs this may not be an option. When this is the case, the within-subject variation may provide a means to establish within-subject changes so that the analyses are not constrained or obscured by the group's differences.

The most important finding from the second investigation was that individuals adapt their movement patterns in response to the demands of a task (64% and 70% of all variables computed were significantly influenced by changing the load and speed, respectively), and quite often in a manner unique to the task or type of demand (e.g. magnitude of load) in question; during the first phase of each task, there were 246 "meaningful" negative adaptations observed in response to an increase in speed, but only 125 in response to the heavier loads. It is not uncommon to assume that an individual's movement patterns reflect their abilities (e.g. joint mobility, flexibility, strength and endurance), or what they can do, nor is it incorrect to do so. However, in most cases an individual does not adopt a particular movement strategy because they can; their movement behavior is likely a reflection of multiple factors such as their perception of risk, awareness or understanding of the task. Many movement evaluations or pre-participation screens are designed to evaluate individuals' movement patterns while they perform a battery of low-demand activities and the findings are used to guide personalized recommendations for training. But rarely are distinctions made between what the individual can do and their habitual motion, if in fact it is even possible. Simply because an individual can perform a particular task in a certain way (given specific instructions in a controlled setting) does not mean that they will perform in a similar manner when in the unpredictable environment of their occupation, sport or life, or if given an opportunity to perform the same task without external- or internal-focused instruction. They may in fact have the ability to move in a manner that would be perceived as "good", but simply do not for any of the reasons described previously. If injury prediction is the desired outcome of movement screening, it may be more important to evaluate individuals' "ingrained" movement patterns rather than what they can do when given task instructions or feedback. Furthermore, if coaching is provided there is no guarantee that an individual's interpretation of the feedback will elicit a movement strategy that only reflects their abilities. It is possible that many individuals described as moving "poorly" may simply require better coaching or a different set of task instructions. Lastly, it is important to highlight that no single movement evaluation or pre-participation screen can be used to interpret an individual's capacity. Movement is not a quality that can be evaluated once prior to the development of a long-term training program and set aside while the intervention is administered. This thesis showed that an individual's movement patterns are variable and influenced by the task and environmental constraints (e.g. speed of movement). Therefore, every exercise, training session or activity of daily living is as an opportunity to observe an individual's movement patterns and can provide valuable information to guide the most appropriate recommendations for training; the challenge lies in identifying the critical observations or "key features" of relevance.

Every task, activity or exercise is unique and can be performed with a variety of movement strategies, many of which would be perceived as "good". In other words, there is no single pattern that should be deemed optimal for every individual. But this does not imply that each task should also be characterized using a different set of criteria; general observations are essential to improve the utility of most movement-based evaluations and interventions, whether formal or not. If every task were described with different "grading" criteria, it would be extremely difficult to generalize any findings to a novel exercise, or a different set of activities that might be more relevant to the individual's life demands. Although it has not been explicitly stated, or shown, that there are "key features" of an individual's movement patterns that can be used to evaluate the quality of their task performance, it may be for this reason that a group of professionals with diverse backgrounds and experiences (e.g. coach, physical therapist and biomechanist), could each perceive the same movement pattern to be "bad". Each professional may not be able to articulate the exact reason for their judgment, yet they would attest to the fact that there was "something" about the individual's motion that prevented them from describing the adopted pattern as "good". This "key feature" approach to the description of movement could provide scientists and practitioners with an opportunity to assess an individual's risk of non-contact musculoskeletal injury without testing a variety of high-risk, physically demanding tasks. The results from the third study of this thesis showed that a battery of general tasks, chosen strategically to challenge participants' capacity to avoid spine and frontal plane knee motion (i.e. the "key features" of interest in this investigation), could be used to estimate the range of deviation adopted while performing select firefighting skills. If participants' gross movement strategies had been described using unique criteria, including temporal and spatial descriptors of motion, complex statistical analyses would likely have been needed to make any task comparisons, because visually, every pattern was different. Instead, the abovementioned joint motions were identified as "key features" that may influence participants' safety and effectiveness (e.g. frontal plane knee motion has been cited as a mechanism for injury), which provided an opportunity to make simple task comparisons between seemingly different movement patterns. Although much more evidence will be needed to substantiate the description of a particular pattern as a "key feature", this approach could also help to establish evidence-based targets for coaches and guide their recommendations for training.

Several conclusions can be drawn from the findings of this thesis, although the most practical and perhaps influential was that a well-designed exercise program can change an individual's habitual movement behaviour. A group of firefighters with little knowledge or appreciation for how they move, exhibited more control and coordination while performing five whole-body transfer tasks following twelve weeks of training. The degree to which training transferred was individual- and task-specific; however, approximately half of all the firefighters who participated in this movement-oriented fitness program exhibited adaptations that could be described as biologically significant. And remarkably, this training effect was captured by characterizing the firefighters' movement patterns with select "key features" (i.e. spine and frontal plane knee motion), lending support to the notion that there are general attributes of an individual's movement behaviour that are common to a variety of tasks or exercises. But perhaps even more intriguing was the fact that these same "key features" could distinguish the adaptations seen following a fitness-oriented intervention, whereby strength, endurance, aerobic capacity, etc. were emphasized in the absence of movement-based feedback, from those experienced by the movement-trained firefighters described above. Both training groups showed tremendous improvements in every aspect of fitness tested, but the fitness-trained firefighters exhibited a propensity to adopt more spine and frontal plane knee motion while performing each of the transfer tasks; they may have actually increased their risk of future injury following the twelve weeks of training. Given the range of abilities and prior experiences amongst either group, it is unlikely that every firefighter's training response can be attributed to any one aspect of their program's design or implementation. There is no single exercise or coaching cue that can be used to improve every individual's capacity; each is simply a tool at the coach's disposal to help them achieve a particular objective. However, one inappropriate recommendation can negate every potential benefit that a program can offer, and therefore, critical to the establishment of a worker-centered framework to physically prepare firefighters is an appreciation for movement and the transfer of training.

7.1. FUTURE RECOMMENDATIONS

This thesis has provided a first step towards the creation of a worker-centered approach to the prevention of musculoskeletal injuries and the physical preparation of high-risk occupational groups such as firefighters, soldiers and police officers; however, much more work is needed to understand how and why individuals adapt their movement behaviour in response to various task and environmental constraints or exercise-based interventions. Changing an individual's movement behaviour is a complex process influenced by numerous factors, of which only a select few were examined in this thesis. Therefore, there is a need to explore the utility of various feedback, instruction and coaching protocols so that scientists and practitioners are able to design evidence-based interventions that impact the transfer and retention of training. Although the findings of this thesis do provide evidence to suggest that the training programs investigated did elicit a transfer in approximately half of all participants, the tasks tested were limited to general patterns of limited demands. Future work should seek to examine the influence of exercise on various complex job-specific skills and activities of daily living.

Because the analyses used in this thesis were limited to select discrete measures, there is also a need to devise a means of quantifying the coordination and control strategies used to perform whole-body tasks. Valuable information related to the temporal and/or spatial characteristics of a pattern may be lost when a peak or mean is used to represent a particular dependent variable. This work could facilitate an opportunity to identify "key features" that comprise individuals' gross movement strategies and help to substantiate the use of participants' variability to describe biologically significant, or "meaningful" changes; or conversely, uncover a more effective means to establish boundary criteria with which individual differences could be described. Establishing a viable means to describe within-subject changes would also afford an opportunity to categorize a study's participants with regards to their baseline movement patterns or adaptations to training.

Much was also said regarding the heterogeneity of participants and the possible limitations of group designs. However, any mention to the unique adaptations and subject-specific responses was not meant to imply that there is little value in looking at the group's behaviour. In fact, there may tremendous benefit, particularly when seeking to establish change amongst a population. The findings of this thesis simply highlight the notion that every individual will not respond or adapt their movement behaviour to a particular stimulus in the exact same manner. Therefore when devising interventions, feedback, exercise or otherwise, it will be important to acknowledge the potential variability amongst the group. The analyses of this thesis were limited to single variables and subject-specific responses in order to examine the variation amongst individuals' behaviour; however, it is possible that clustering participants and conducting multivariate regressions could have provided further insight into the most effective training strategies for a particular demographic, or conversely, helped to establish a rationale as to why certain individuals adapted in a particular manner. Or perhaps simply a first step. An individual's movement behaviour is influenced by many factors including their strength, endurance, previous experiences, awareness, attitude, perception of risk, and understanding of the task, implying that cross-disciplinary work is probably needed to predict and prevent musculoskeletal injuries.

The fact that the movement-trained firefighters exhibited less spine and frontal plane knee while performing each transfer task is extremely promising with regards to the prevention of future musculoskeletal injury; however, any discussion pertaining to an individual's risk may be premature. Because this thesis was limited to an evaluation of movement patterns, assumptions were made regarding the relationship between various joint motions, tissue loading and individuals' risk of injury. Although each assumption was based on previous work that has documented the mechanics of injury, it would be incredibly valuable to examine the observed forces, moments and muscle activation patterns so that each individual's movement patterns could be contrasted to the loads imposed on a particular joint. Therefore, it is recommended that future work seek to explore the relationship between each factor, both before and after training. Musculoskeletal injuries are influenced by force, repetition and posture (movement) and thus simply because an individual adopts a particular movement behaviour does not imply that they will be at increased risk. Joint motion in the absence of force and repetition may not provide an exposure of concern given that the corresponding joint compression and shear could be of a magnitude that will not cause harm. However, the same can be said of loading. High compressive loads in the absence of joint motion may not be of concern if the mechanism for the injury of interest is shear. As such, it could be argued that the most conservative approach to the prevention of musculoskeletal injuries is to gauge risk via individuals' movement behaviour. Describing a pattern as high risk when in fact it is not, given the magnitude of loading, is more responsible than assuming the individual is safe when their pattern reflects a habitual behavior that will be adopted to perform a range of activities of varying demands. However, there is only way to truly evaluate the effectiveness of an intervention designed to physically prepare high-risk occupational groups such firefighters, police officers or soldiers – conduct a prospective study, whereby a long-term commitment is made to track the incidence of injury, while periodically assessing the individuals' capacity to perform the activities relevant to the demands of their lives.

References

Adams, T.D., Yanowitz, F.G., Chandler, S., Specht, P., Lockwood, R. and Yeh, M.P. (1986). A study to evaluate and promote total fitness among fire fighters. *Journal of Sports Medicine and Physical Fitness,* 26**,** 337-345.

Albert, D. (2009). An investigation into the prevalence and risk factors of occupational musculoskeletal injuries in firefighters in the Durban Metropolitan Fire Department. Masters Degree in Chiropractic, Durban University of Technology.

Almeida, S.A., Williams, K.M., Shaffer, R.A. and Brodine, S.K. (1999). Epidemiological patterns of musculoskeletal injuries and physical training. *Medicine and Science in Sports and Exercise,* 31**,** 1176-1182.

Baker, D. (1996). Improving vertical jump through general, special, and specific strength training: A brief review. *Journal of Strength and Conditioning Research,* 10**,** 131-136.

Baker, D., Wilson, G. and Carlyon, B. (1994). Generality versus specificity: A comparison of dynamic and isometric measures of strength and speed strength. *European Journal of Applied Physiology,* 68**,** 350-355.

Bartlett, R., Wheat, J. and Robins, M. (2007). Is movement variability important for sports biomechanists? *Sports Biomechanics,* 6**,** 224-243.

Bates, B.T. (1996). Single-subject methodology: an alternative approach. *Medicine and Science in Sports and Exercise,* 28**,** 631-638.

Bates, B.T., Dufek, J.S. and Davis, H.P. (1992). The effect of trial size on statistical power. *Medicine and Science in Sports and Exercise,* 24**,** 1059-1065.

Bates, B.T., Hamill, J. and Devita, P. (1988). The evaluation of strategies used to accommodate additional loads during running. *Proceeding of the 5th Biennial Conference of the Canadian Society for Biomechanics*, Ottawa, Ontario.

Bates, B.T., Osternig, L.R., Sawhill, J.A. and James, S.L. (1983). An assessment of subject variability, subject-shoe interaction, and the evaluation of running shoes using ground reaction force data. *Journal of Biomechanics,* 16**,** 181-191.

Batterham, A.M. and Hopkins, W.G. (2006). Making meaningful inferences about magnitudes. *International Journal of Sports Physiology and Performance,* 1**,** 50-57.

Begon, M., Monnet, T. and Lacouture, P. (2007). Effects of movement for estimating the hip joint centre. *Gait and Posture,* 25**,** 353-359.

Beiring-Sorensen, F. (1984). Physical measurements as risk indicators for low-back trouble over a one-year period. *Spine,* 9**,** 106-119.

Bernstein, N. (1967). *The co-ordination and regulation of movements.*, Pergamon Press.

Blazevich, A.J., Gill, N. and Newton, R.U. (2002). Reliability and validity of two isometric squat tests. *Journal of Strength and Conditioning Research,* 16**,** 298-304.

Bradley, P.S. and Portas, M.D. (2007). The relationship between preseason range of motion and muscle strain injury in elite soccer players. *Journal of Strength and Conditioning Research,* 21**,** 1155-1159.

Broderick, M.P. and Newell, K.M. (1999). Coordination patterns in ball bouncing as a function of skill. *Journal of Motor Behaviour,* 31**,** 165-188.

Bureau of Labor Statistics. U.S. Department of Labor 2009. Workplace injuries and illnesses - 2008.

Burton, S.L. (2006). Performance and injury predictability during firefighter candidate training. *Doctoral Dissertation*, Virginia Tech.

Cady, L.D., Bischoff, D.P., O'Connell, E.R., Thomas, P.C. and Allan, J.H. (1979). Strength and fitness and subsequent back injuries in firefighters. *Journal of Occupational Medicine,* 21**,** 269-272.

Caillou, N., Nourrit, D., Deschamps, T. and Lauriot, B. (2002). Overcoming spontaneous patterns of coordination during the acquisition of a complex balancing task. *Canadian Journal of Experimental Psychology,* 56**,** 283-293.

Callaghan, J.P. and McGill, S.M. (2001). Intervertebral disc herniation: studies on a porcine model exposed to highly repetitive flexion/extension motion with compressive force. *Clinical Biomechanics,* 16**,** 28-37.

Carlock, J.M., Smith, S.L., Hartman, M.J., Morris, R.T., Ciroslan, D.A., Pierce, K.C., Newton, R.U., Harman, E.A., Sands, W.A. and Stone, M.H. (2004). The relationship between vertical jump power estimates and weightlifting ability: A field test approach. *Journal of Strength and Conditioning Research,* 18**,** 534-539.

Carroll, T.J., Riek, S. and Carson, R.G. (2001). Neural adaptations to resistance training: implications for movement control. *Sports Medicine,* 31**,** 829-840.

Caster, B.L. and Bates, B.T. (1995). The assessment of mechanical and neuromuscular response strategies during landing. *Medicine and Science in Sports and Exercise,* 27**,** 736-744.

Chaudhari, A.M. and Andriacchi, T.P. (2006). The mechanical consequences of dynamic frontal plane limb alignment for non-contact ACL injury. *Journal of Biomechanics,* 39**,** 330-338.

Cole, G.K., Nigg, B.M., Ronsky, J.L. and Yeardon, M.R. (1993). Application of the joint coordinate system to three-dimensional joint attitude and movement representation: a standardization proposal. *Journal of Biomechanical Engineering,* 115**,** 344-349.

Cook, G., Burton, L. and Hoogenboom, B. (2006a). Pre-participation screening: The use of fundamental movements as an assessment of function - Part 1. *North American Journal of Sports Physical Therapy,* 1**,** 62-72.

Cook, G., Burton, L. and Hoogenboom, B. (2006b). Pre-participation screening: The use of fundamental movements as an assessment of function - Part 2. *North American Journal of Sports Physical Therapy,* 1**,** 132-139.

Cotterman, M.L., Darby, L.A. and Skelly, W.A. (2005). Comparison of muscle force production using the smith machine and free weights for bench press and squat exercises. *Journal of Strength and Conditioning Research,* 19**,** 169-176.

Cowling, E.J., Steele, J.R. and McNair, P.J. (2003). Effect of verbal instructions on muscle activity and risk of injury to the anterior cruciate ligament during landing. *British Journal of Sports Medicine,* 37**,** 126-130.

Davids, K., Glazier, P., Araujo, D. and Bartlett, R. (2003). Movement systems as dynamical systems: the functional role of variability and its implications for sports medicine. *Sports Medicine,* 33**,** 245-260.

Davis, K.G. and Seol, H. (2005). Injury-induced kinematic compensations within the lower back: impact of non-lower back injuries. *Ergonomics,* 48**,** 135-149.

Dempsey, A.R., Lloyd, D.G., Elliott, B.C., Steele, J.R. and Munro, B.J. (2009). Changing sidestep cutting technique reduces knee valgus loading. *The American Journal of Sports Medicine,* 37**,** 2194-2200.

DeVita, P. and Bates, B.T. (1988). Intraday reliability of ground reaction force data. *Human Movement Science,* 7**,** 73-85.

DiStefano, L.J., Padua, D.A., Distefano, M.J. and Marshall, S.W. (2009). Influence of age, sex, technique, and exercise program on movement patterns after an anterior cruciate ligament injury prevention program in youth soccer players. *The American Journal of Sports Medicine,* 37**,** 495-505.

Dufek, J.S. and Bates, B.T. (1990). The evaluation and prediction of impact forces during landings. *Medicine and Science in Sports and Exercise,* 22**,** 370-377.

Dufek, J.S., Bates, B.T., Stergiou, N. and James, C.R. (1995). Interactive effects between group and single-subject reponse patterns. *Human Movement Science,* 14**,** 301-323.

Dunk, N.M., Keown, K.J., Andrews, D.M. and Callaghan, J.P. (2005). Task variability and extrapolated cumulative low back loads. *Occupational Ergonomics,* 5**,** 149-159.

Elsner, K.L. and Kolkhorst, F.W. (2008). Metabolic demands of simulated firefighting tasks. *Ergonomics,* 51**,** 1418-1425.

Findley, B.W., Brown, L.E., Whitehurst, M., Gilbert, R. and Apold, S.A. (1995). Age-group performance and physical fitness in male firefighters. *Journal of Strength and Conditioning Research,* 9**,** 259-260.

Flanagan, S.P. and Salem, G.J. (2008). Lower extremity joint kinetic responses to external resistance variations. *Journal of Applied Biomechanics,* 24**,** 58-68.

Frost, D., Andersen, J., Lam, T., Finlay, T., Darby, K. and McGill, S. (2012a). The relationship between general measures of fitness, pasive range of motion and whole-body movement quality. *Ergonomics,* Epub ahead of print.

Frost, D.M., Gooyers, C.E., Campbell, T.L., McGill, S.M. and Callaghan, J.P. (2012b). Does the elimination of thigh markers influence the between-day variation in joint angles? *Proceeding of the 17th Biennial Conference of the Canadian Society for Biomechanics*, Vancouver, British Columbia.

Frost, D.M., Gooyers, C.E., Campbell, T.L., McGill, S.M. and Callaghan, J.P. (2012c). Might the interpretation of between-day changes in joint angles, forces and moments be influenced by variation in the link segment model? *Proceeding of the 17th Biennial Conference of the Canadian Society for Biomechanics*, Vancouver, British Columbia.

Fry, A.C., Smith, J.C. and Schilling, B.K. (2003). Effect of knee position on hip and knee torques during the barbell squat. *Journal of Strength and Conditioning Research,* 17**,** 629-633.

Gerkin, R., Kelley, P. and Perry, R. (1997). Correlation of VO2max during maximal treadmill stress testing with VO2 at 85% predicted maximal heart rate: a retrospective review of the Phoenix Fire Department treadmill protocol. *Technical Report to the Medical Director of the Phoenix Fire Department Medical Center*, 1-4.

Goss, D.L., Christopher, G.E., Faulk, R.T. and Moore, J. (2009). Functional training program bridges rehabilitation and return to duty. *Journal of Special Operations Medicine,* 9**,** 29-48.

Granata, K.P., Marras, W.S. and Davis, K.G. (1999). Variation in spinal load and trunk dynamics during repeated lifting exertions. *Clinical Biomechanics,* 14**,** 367-375.

Greska, E.K., Cortes, N., Van Lunen, B.L. and Onate, J.A. (2012). A feedback inclusive neuromuscular training program alters frontal plane kinematics. *Journal of Strength and Conditioning Research,* 26**,** 1609-1619.

Grills, P.M., Mientjes, M., Wells, R., Norman, R., Neumann, P., Frank, J. and Shannon, H. (1994). The reliability and variability of low back physical exposure measures. *Proceeding of the 12th Triennial Congress of the International Ergonomics Association*, Toronto, Ontario.

Hamill, J. and McNiven, S.L. (1990). Reliability of selected ground reaction force parameters during walking. *Human Movement Science,* 9**,** 117-131.

Hamill, J., van Emmerik, R.E.A., Heiderscheit, B.C. and Li, L. (1999). A dynamical systems approach to lower extremity running injuries. *Clinical Biomechanics,* 14**,** 297-308.

Harris-Hayes, M. and Van Dillen, L.R. (2009). The inter-tester reliability of physical therapists classifying low back pain problems based on the Movement System Impairment Classification System. *PM&R,* 1**,** 117-126.

Hatze, H. (1986). Motion variability - its definition, quantification, and origin. *Journal of Motor Behaviour,* 18**,** 5-16.

Herman, D.C., Onate, J.A., Weinhold, P.S., Guskiewicz, K.M., Garrett, W.E., Yu, B. and Padua, D.A. (2009). The effects of feedback with and without strength training on lower extremity biomechanics. *The American Journal of Sports Medicine,* 37**,** 1301-1308.

Herman, D.C., Weinhold, P.S., Guskiewicz, K.M., Garrett, W.E., Yu, B. and Padua, D.A. (2008). The effects of strength training on the lower extremity biomechanics of female recreational athletes during a stop-jump task. *The American Journal of Sports Medicine,* 36**,** 733-740.

Hewett, T.E., Lindenfeld, T.N., Riccobene, J.V. and Noyes, F.R. (1999). The effect of neuromuscular training on the incidence of knee injury in female athletes: a prospective study. *The American Journal of Sports Medicine,* 27**,** 699-706.

Hewett, T.E., Myer, G.D., Ford, K.R., Heidt, R.S., Colosimo, A.J., McLean, S.G., van den Bogert, A.J., Paterno, M.V. and Succop, P. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *The American Journal of Sports Medicine,* 33**,** 492-501.

Hewett, T.E., Stroupe, A.L., Nance, T.A. and Noyes, F.R. (1996). Plyometric training in female athletes: decreased impact forces and increased hamstring torques. *The American Journal of Sports Medicine,* 24**,** 765-773.

Hewett, T.E., Torg, J.S. and Boden, B.P. (2009). Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral trunk and knee abduction motion are combined components of the injury mechanism. *British Journal of Sports Medicine,* 43**,** 417-422.

Hilyer, J.C., Brown, K.C., Sirles, A.T. and Peoples, L. (1990). A flexibility intervention to reduce the incidence and severity of joint injuries among municipal firefighters. *Journal of Occupational Medicine,* 32**,** 631-637.

Hoover, D., Killian, C.B., Bourcier, B., Lewis, S., Thomas, J. and Willis, R. (2008). Predictive validity of the Functional Movement Screen in a population of recreational runners training for a half marathon. *Proceeding of the 55th Annual Meeting of the American College of Sports Medicine*, Indianapolis, Indiana.

Hopkins, W. (2000). Measures and reliability in sports medicine and science. *Sports Medicine* 30**,** 1-15.

Howarth, S.J. (2011). Mechanical response of the porcine cervical spine to acute and repetitive anterior-posterior shear. *Doctoral Dissertation*, University of Waterloo.

Howarth, S.J. and Callaghan, J.P. (2009). The rule of 1s for padding kinematic data prior to digital filtering: Influence of sampling and filter cutoff frequencies. *Journal of Electromyography and Kinesiology,* 19**,** 875-881.

International Association of Fire Fighters *The IAFF/IAFC Fire Service Joint Labor Management Candidate Physical Ability Test program summary.* [Online]. Available: http://www.iaff.org/hs/CPAT/cpat_index.html [Accessed July 30 2010].

James, C.R. and Bates, B.T. (1997). Experimental and statistical design issues in human movement research. *Measurement in Physical Education and Exercise Science,* 1**,** 55-69.

James, C.R., Herman, J.A., Dufek, J.S. and Bates, B.T. (2007). Number of trials necessary to achieve performance stability of selected ground reaction force variables during landing. *Journal of Sports Science and Medicine,* 6**,** 126-134.

Jones, B.H., Bovee, M.W., Harris III, J. and Cowan, D.N. (1993a). Intrinsic risk factors for exercise-related injuries among male and female army trainees. *The American Journal of Sports Medicine,* 2**,** 705-710.

Jones, B.H., Cowan, D.N., Tomlinson, J.P., Robinson, J.R., Polly, D.W. and Frykman, P.N. (1993b). Epidemiology of injuries associated with physical training among young men in the Army. *Medicine and Science in Sports and Exercise,* 25**,** 197-203.

Karter Jr, M.J. (2012). Patterns of firefighter fireground injuries. National Fire Protection Association

Karter Jr, M.J. and Molis, J.L. (2010). U.S. Firefighter Injuries - 2009. National Fire Protection Association.

Kernozek, T., Iwasaki, M., Fater, D. and Durall, C. (2006). Movement-based feedback may reduce spinal moments in male workers during lifting and lowering tasks. *Physiotherapy Research International,* 11**,** 140-147.

Kiesel, K., Plisky, P. and Butler, R. (2011). Functional movement test scores improve following a standardized off-season intervention program in professional football players. *Scandinavian Journal of Medicine and Science in Sports,* 21**,** 287-292.

Kiesel, K., Plisky, P.J. and Voight, M.L. (2007). Can serious injury in professional football be predicted by a preseason functional movement screen? *North American Journal of Sports Physical Therapy.,* 2**,** 147-158.

Kiesel, K.B., Butler, R.J. and Plisky, P.J. (2010). Results of a training program designed to improve fundamental movement patterns in professional football players. *Proceeding of the 57th Annual Meeting of the American College of Sports Medicine*, Balitmore, Maryland.

King, D., Hannon, J. and Shoup, E. (2009). Effect of technique on knee, hip, and L5/S1 net moments in the parallel back squat. *Proceeding of the 33rd Annual Meeting of the American Society of Biomechanics*, State College, Pennsylvania.

Kjellberg, K., Lindbeck, L. and Hagberg, M. (1998). Method and performance: two elements of work technique. *Ergonomics,* 41**,** 798-816.

Knapik, J.J., Bauman, C.L., Jones, B.H., Harris, J.M. and Vaughan, L. (1991). Preseason strength and flexibility imbalances associated with athletic injuries in female collegiate athletes. *The American Journal of Sports Medicine,* 19**,** 76-81.

Knapik, J.J., Bullock, S.H., Canada, S., Toney, E., Wells, J.D., Hoedebecke, E. and Jones, B.H. (2004). Influence of an injury reduction program on injury and fitness outcomes among soldiers. *Injury Prevention,* 10**,** 37-42.

Knapik, J.J., Sharp, M.A., Canham-Chervak, M., Hauret, K., Patton, J.F. and Jones, B.H. (2001). Risk factors for training-related injuries among men and women in basic combat training. *Medicine and Science in Sports and Exercise,* 33**,** 946-954.

Knutson, G.A. (2005). Anatomic and functional leg-length inequality: A review and recommendation for clinical decision-making. Part I, anatomic leg-length inequality: prevalence, magnitude, effects and clinical significance. *Chiropractic & Osteopathy,* 13.

Koyanagi, M., Shino, K., Yoshimoto, Y., Inoue, S., Sato, M. and Nakata, K. (2006). Effects of changes in skiing posture on the kinetics of the knee joint. *Knee Surgery, Sports Traumatology, Arthroscopy,* 14**,** 88-93.

Kritz, M., Cronin, J. and Hume, P. (2009a). The bodyweight squat: A movement screen for the squat pattern. *Strength and Conditioning Journal,* 31**,** 76-85.

Kritz, M., Cronin, J. and Hume, P. (2009b). Using the body weight forward lunge to screen an athlete's lunge pattern. *Strength and Conditioning Journal,* 31**,** 15-24.

Kritz, M., Cronin, J. and Hume, P. (2010). Screening the upper-body push and pull patterns using body weight exercises. *Strength and Conditioning Journal,* 32**,** 72-82.

Kulas, A.S., Hortobagyi, T. and Devita, P. (2010). The interaction of trunk-load and trunk-position adaptations on knee anterior shear and hamstrings muscle forces during landing. *Journal of Athletic Training,* 45**,** 5-15.

Kulic, D., Venture, G. and Nakamura, Y. (2009). Detecting changes in motion characteristics during sports training. *Proceeding of the 31st Annual International Conference of the IEEE EMBS*, Minneapolis, Minnesota.

Lavender, S.A., Lorenz, E.P. and Andersson, G.B.J. (2007). Can a new behaviorally oriented training process to improve lifting technique prevent occupationally related back injuries due to lifting? *Spine,* 32**,** 487-494.

Lenaerts, G., Mulier, M., Spaepen, A., Van der Perre, G. and Jonkers, I. (2009). Aberrant pelvis and hip kinematics impair hip loading before and after total hip replacement. *Gait & Posture,* 30**,** 296-302.

Lindsay, D. and Horton, J. (2002). Comparison of spine motion in elite golfers with and without low back pain. *Journal of Sports Sciences,* 20**,** 599-605.

Lubahn, A.J., Kerbozek, T.W., Tyson, T.L., Merkitch, K.W., Reutemann, P. and Chestnut, J.M. (2011). Hip muscle activation and knee frontal plane motion during weight bearing therapeutic exercises. *International Journal of Sports Physical Therapy,* 6**,** 92-103.

Ludewig, P.M. and Cook, T.M. (2000). Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement. *Physical Therapy,* 80**,** 276-291.

Mandelbaum, B.R., Silvers, H.J., Watanabe, D.S., Knarr, J.F., Thomas, S.D., Griffin, L.Y., Kirkendall, D.T. and Garrett Jr, W. (2005). Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. *The American Journal of Sports Medicine,* 33**,** 1003-1010.

Marras, W.S., Lavender, S.A., Leurgans, S.E., Rajulu, S.L., Allread, W.G., Fathallah, F.A. and Ferguson, S.A. (1993). The role of dynamic three-dimensonal trunk motion in occupationally-related low back disorders. The effects of workplace factors, trunk position, and trunk motion characteristics on risk of injury. *Spine,* 18**,** 617-628.

Marshall, L.W. and McGill, S.M. (2010). The role of axial torque in disc herniation. *Clinical Biomechanics,* 25**,** 6-9.

Mathiassen, S.E., Moller, T. and Forsman, M. (2003). Variability in mechanical exposure within and between individuals performing a highly constrained industrial work task. *Ergonomics,* 46**,** 800-824.

McGill, S., Grenier, S., Bluhm, M., Preuss, R., Brown, S. and Russell, C. (2003). Previous history of LBP with work loss is related to lingering deficits in biomechanical, physiological, personal, psychosocial and motor control characteristics. *Ergonomics,* 46**,** 731-746.

McGill, S.M. (1988). Estimation of force and extensor moment contributions of the disc and ligaments at L4-L5. *Spine,* 13**,** 1395-1402.

McGill, S.M. (1998). Low back exercises: Evidence for improving exercise regimens. *Physical Therapy,* 78**,** 754-765.

McGill, S.M., Hughson, R.L. and Parks, K. (2000). Changes in lumbar lordosis modify the role of the extensor muscles. *Clinical Biomechanics,* 15**,** 777-780.

McGinn, P.A. (2004). Effects of a 6-week strength-training program on landing kinematics and kinetics of female collegiate basketball athletes. *Doctoral Dissertation*, University of Kentucky.

McKean, M.R., Dunn, P.K. and Burkett, B.J. (2010). Quantifying the movement and the influence of load in the back squat exercise. *Journal of Strength and Conditioning Research,* 24**,** 1671-1679.

McNair, P.J., Prapavessis, H. and Callender, K. (2000). Decreasing landing forces: effect of instruction. *British Journal of Sports Medicine,* 34**,** 293-296.

Michaelides, M.A., Parpa, K.M., Henry, L.J., Thompson, G.B. and Brown, B.S. (2011). Assessment of physical fitness aspects and their relationship to firefighters' job abilities. *Journal of Strength and Conditioning Research,* 25**,** 956-965.

Mirka, G.A. and Baker, A. (1996). An investigation of the variability in human performance during sagittally symmetric lifting tasks. *IIE Transactions,* 28**,** 745-752.

Moreside, J.M. (2010). The effect of limited hip mobility on the lumbar spine in a young adult population. *Doctoral Dissertation*, University of Waterloo.

Morriss, C., Bartlett, R.M. and Fowler, N. (1997). Biomechanical analysis of the men's javelin throw at the 1995 World Championships in Athletics. *New Studies in Athletics,* 12**,** 31-41.

Mottram, S. and Comerford, M. (2008). A new perspective on risk assessment. *Physical Therapy,* 9**,** 40-51.

Myer, G.D., Ford, K.R., Brent, J.L. and Hewett, T.E. (2007). Differential neuromuscular training effects on ACL injury risk factors in "high-risk" versus "low-risk" athletes. *BMC Musculoskeletal Disorders,* 8.

Myer, G.D., Ford, K.R., Brent, J.L. and Hewett, T.E. (2012). An integrated approach to change the outcome Part II: Targeted neuromuscular training techniques to reduce identified ACL injury risk factors. *Journal of Strength and Conditioning Research,* 26**,** 2272-2292.

Myer, G.D., Ford, K.R., McLean, S.G. and Hewett, T.E. (2006). The effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics. *The American Journal of Sports Medicine,* 34**,** 445-455.

Myers, C.A. and Hawkins, D. (2010). Alterations to movement mechanics can greatly reduce anterior cruciate ligament loading without reducing performance. *Journal of Biomechanics,* 43**,** 2657-2664.

Nadler, S.F., Malanga, G.A., Bartoli, L.A., Feinberg, J.H., Prybicien, M. and DePrince, M. (2002). Hip muscle imbalance and low back pain in athletes: influence of core strengthening. *Medicine and Science in Sports and Exercise,* 34**,** 9-16.

Newell, K.M. (2009). Change in movement and skill: Learning, retention, and transfer. *In:* LATASH, M.L. and TURVEY, M.T. (eds.) *Dexterity and its development.* New Jersey: Taylor and Francis.

Newell, K.M. and Vaillancourt, D.E. (2001). Dimensional change in motor learning. *Human Movement Science,* 20**,** 695-715.

Noehren, B., Scholz, J. and Davis, I. (2011). The effect of real-time gait retraining on hip kinematics, pain and function in subjects with patellofemoral pain syndrome. *British Journal of Sports Medicine,* 45**,** 691-696.

Norman, R., Wells, R., Neumann, P., Frank, J., Shannon, H. and Kerr, M. (1998). A comparison of peak vs cumulative physical work exposure risk factors for the reporting of low back pain in the automotive industry. *Clinical Biomechanics,* 13**,** 561-573.

Noyes, F.R., Barber-Weestin, S.D., Fleckenstein, C., Walsh, C. and West, J. (2005). The drop-jump screening test: difference in lower limb control by gender and effect of neuromuscular training in female athletes. *The American Journal of Sports Medicine,* 33**,** 197-207.

Noyes, F.R., Barber-Westin, S.D., Smith, S.T., Campbell, T. and Garrison, T.T. (2012). A training program to improve neuromuscular and performance indices in female high school basketball players. *Journal of Strength and Conditioning Research,* 26**,** 709-719.

Okada, T., Huxel, K.C. and Nesser, T.W. (2011). Relationship between core stability, functional movement, and performance. *Journal of Strength and Conditioning Research,* 25**,** 252-261.

Onate, J.A., Guskiewicz, K.M., Marshall, S.W., Giuliani, C., Yu, B. and Garrett, W.E. (2005). Instruction of jump-landing technique using videotape feedback: altering lower extremity motion patterns. *The American Journal of Sports Medicine,* 33**,** 831-842.

Papa, E. and Cappozzo, A. (2000). Si-to-stand motor strategies investigated in able-bodied young and elderly subjects. *Journal of Biomechanics,* 33**,** 1113-1122.

Peate, W.F., Bates, G., Lunda, K., Francis, S. and Bellamy, K. (2007). Core strength: A new model for injury prediction and prevention. *Journal of Occupational Medicine and Toxicology,* 2**,** 1-9.

Peh, S.Y.C., Chow, J.Y. and Davids, K. (2011). Focus of attention and its impact on movement behaviour. *Journal of Science and Medicine in Sport,* 14**,** 70-78.

Pfeiffer, R.P., Shea, K.G., Roberts, D., Grandstrand, S. and Bond, L. (2006). Lack of effect of a knee ligament injury prevention program on the incidence of noncontact anterior cruciate ligament injury. *The Journal of Bone and Joint Surgery,* 88**,** 1769-1774.

Plisky, P.J., Rauh, M.J., Kaminski, T.W. and Underwood, F.B. (2006). Star excursion balance test as a predictor of lower extremity injury in high school basketball players. *Journal of Orthopaedic and Sports Physical Therapy,* 36**,** 911-919.

Pohl, M.B., Mullineaux, D.R., Milner, C.E., Hamill, J. and Davis, I.S. (2008). Biomechanical predictors of retrospective tibial stress fractures in runners. *Journal of Biomechanics,* 41**,** 1160-1165.

Poplin, G.S., Harris, R.B., Pollack, K.M., Peate, W.F. and Burgess, J.L. (2012). Beyond the fireground: injuries in the fire service. *Injury Prevention,* 18**,** 228-233.

Punnett, L., Fine, L.J., Keyserling, W.M., Herrin, G.D. and Chaffin, D.B. (1991). Back disorders and nonneutral trunk postures of automobile assembly workers. *Scandinavian Journal of Work, Environment and Health,* 17**,** 337-346.

Reilly, T., Morris, T. and Whyte, G. (2009). The specificity of training prescription and physiilogical assessment: A review. *Journal of Sports Sciences,* 27**,** 575-589.

Riechard, A.A. and Jackson, L.L. (2010). Occupational injuries among emergency responders. *American Journal of Industrial Medicine,* 53**,** 1-11.

Roberts, M.A., O'Dea, J., Boyce, A. and Mannix, E.T. (2002). Fitness levels of firefighter recruits before and after a supervised exercise training program. *Journal of Strength and Conditioning Research,* 16**,** 271-277.

Rodano, R. and Squadrone, R. (2002). Stability of selected lower limb joint kinetic parameters during vertical jump. *Journal of Applied Biomechanics,* 18**,** 83-89.

Rucci, J.A. and Tomporowski, P.D. (2010). Three types of kinematic feedback and the execution of the hang power clean. *Journal of Strength and Conditioning Research,* 24**,** 771-778.

Savelberg, H.H.C.M., Fastenau, A., Willems, P.J.B. and Meijer, K. (2007). The load/capacity ratio affects the sit-to-stand movement strategy. *Clinical Biomechanics,* 22**,** 805-812.

Scheaff, A.K. (2009). Physiological determinants of the Candidate Physical Ability Test in firefighters. *Master's Dissertation*, University of Maryland.

Scholes, C.J., McDonald, M.D. and Parker, A.W. (2012). Single-subject analysis reveals variation in knee mechanics during step landing. *Journal of Biomechanics,* 45**,** 2074-2078.

Schwartz, M.H. and Rozumalski, A. (2005). A new method for estimating joint parameters from motion data. *Journal of Biomechanics,* 38**,** 107-116.

Schweim, J.J. (2009). Do any of a set of lower extremity functional assessment tests predict in the incidence of injury among a cohort of collegiate freshman football players? A pilot study. *Master's Dissertation*, The Ohio State University.

Smith, G. (1989). Padding point extrapolation techniques for the Butterworth digital filter. *Journal of Biomechanics* 22**,** 967-971.

Stergiou, N. (2004). *Innovative analyses of human movement*, Human Kinetics.

Straker, L.M. (2003). A review of research on techniques for lifting low-lying objects: 2. Evidence for a correct technique. *Work,* 20**,** 83-96.

Stuelcken, M.C. and Sinclair, P.J. (2009). A pilot study of the front foot ground reaction forces in elite female fast bowlers. *Journal of Science and Medicine in Sport,* 12**,** 258-261.

Swinnen, S.P., Lee, T.D., Verschueren, S., Serrien, D.J. and Bogaerds, H. (1997). Interlimb coordination: Learning and transfer under different feedback conditions. *Human Movement Science,* 16**,** 749-785.

TriData (2004). The economic consequences of firefighter injuries and their prevention. National Institute of Standards and Technology.

Tyler, T.F., Nicholas, S.J., Campbell, R.J. and McHugh, M.P. (2001). The association of hip strength and flexibility with the incidence of adductor muscle strains in professional ice hockey players. *The American Journal of Sports Medicine,* 29**,** 124-128.

van Dieen, J.H., Hoozemans, M.J.M., van der Beek, A.J. and Mullender, M. (2002). Precision of estimates of mean and peak spinal loads in lifting. *Journal of Biomechanics,* 35**,** 979-982.

Van Dillen, L.R., Bloom, N.J., Gombatto, S.P. and Susco, T.M. (2008). Hip rotation range of motion in people with and without low back pain who participate in rotation-related sports. *Physical Therapy in Sport,* 9**,** 72-81.

Vereijken, B., van Emmerik, R.E.A., Whiting, H.T.A. and Newell, K.M. (1992). Free(z)ing degrees of freedom in skill acquisition. *Journal of Motor Behaviour,* 24**,** 133-142.

Walton, S.M., Conrad, K.M., Furner, S.E. and Samo, D.G. (2003). Cause, type and workers' compensation costs of injury to fire fighters. *American Journal of Industrial Medicine,* 43, 454-458.

Waters, T.R., Putz-Anderson, V., Garg, A. and Fine, L.J. (1993). Revised NIOSH equation for the design and evaluation of manual lifting tasks. *Ergonomics,* 36, 749-776.

Williams-Bell, F.M., Boisseau, G., McGill, J., Kostiuk, A. and Hughson, R.L. (2010). Air management and physiological responses during simulated firefighting tasks in a hig-rise structure. *Applied Ergonomics,* 41, 251-259.

Williams-Bell, F.M., Villar, R., Sharratt, M.T. and Hughson, R.L. (2009). Physiological demands of the Firefighter Candidate Physical Ability Test. *Medicine and Science in Sports and Exercise,* 41, 653-662.

Wilson, C., Simpson, S.E., van Emmerik, R.E.A. and Hamill, J. (2008). Coordination variability and skill development in expert triple jumpers. *Sports Biomechanics,* 7, 2-9.

Winchester, J.B., Porter, J.M. and McBride, J.M. (2009). Changes in bar path kinematics and kinetics through use of summary feedback in power snatch training. *Journal of Strength and Conditioning Research,* 23, 444-454.

Winter, D.A. (2005). *Biomechanics and motor control of human movement*, Wiley & Sons Inc.

Witvrouw, E., Danneels, L., Asselman, P., D'Have, T. and Cambier, D. (2003). Muscle flexibility as a risk factor for developing muscle injuries in male professional soccer players. *The American Journal of Sports Medicine,* 31, 41-46.

Woltring, H.J. (1991). Representation and calculation of 3-D joint movement. *Human Movement Science,* 10, 603-616.

Wulf, G. and Prinz, W. (2001). Directing attention to movement effects enhances learning: A review. *Psychonomic Bulletin & Review,* 8, 648-660.

Yuktasir, B. and Kaya, F. (2009). Investigation into the long-term effects of static and PNF stretching exercises on range of motion and jump performance. *Journal of Bodywork and Movement Therapies,* 13, 11-21.

Zajac, F.E. (1989). Determining muscle's force and action in multi-articular movement. *Exercise and Sport Sciences Reviews,* 17, 187-230.

Appendix A

SUPPLEMENT - INVESTIGATION ONE

MOVEMENT VARIABILITY AND THE ESTIMATION OF “MEANINGFUL”CHANGE

Time normalized data illustrating the group’s movement patterns for the lifting and simulated firefighting tasks are presented in Figures A.1 and A.2. Figures A.3, A.4 and A.5 provide time series comparisons for select participants to highlight the individual differences that were seen amongst the firefighters, both in regards to the magnitude of each dependent measure and the between-session variation.

The investigation described in Chapter 3 examined the potential in using the within-subject variation as a criterion with which to define “meaningful” within-subject differences between multiple conditions or testing sessions; however, the results presented were collapsed across all variables. Figures A.6 and A.7 illustrate the number of instances across all metrics and sessions whereby the method was “successful” (defined as the number of instances whereby the sequential within-subject variation was larger than the 25-trial mean – sequential mean difference) for each variable investigated. In general, the utility of the approach appeared to be similar across each of the dependent measures.

A.1.1. Group Behaviour

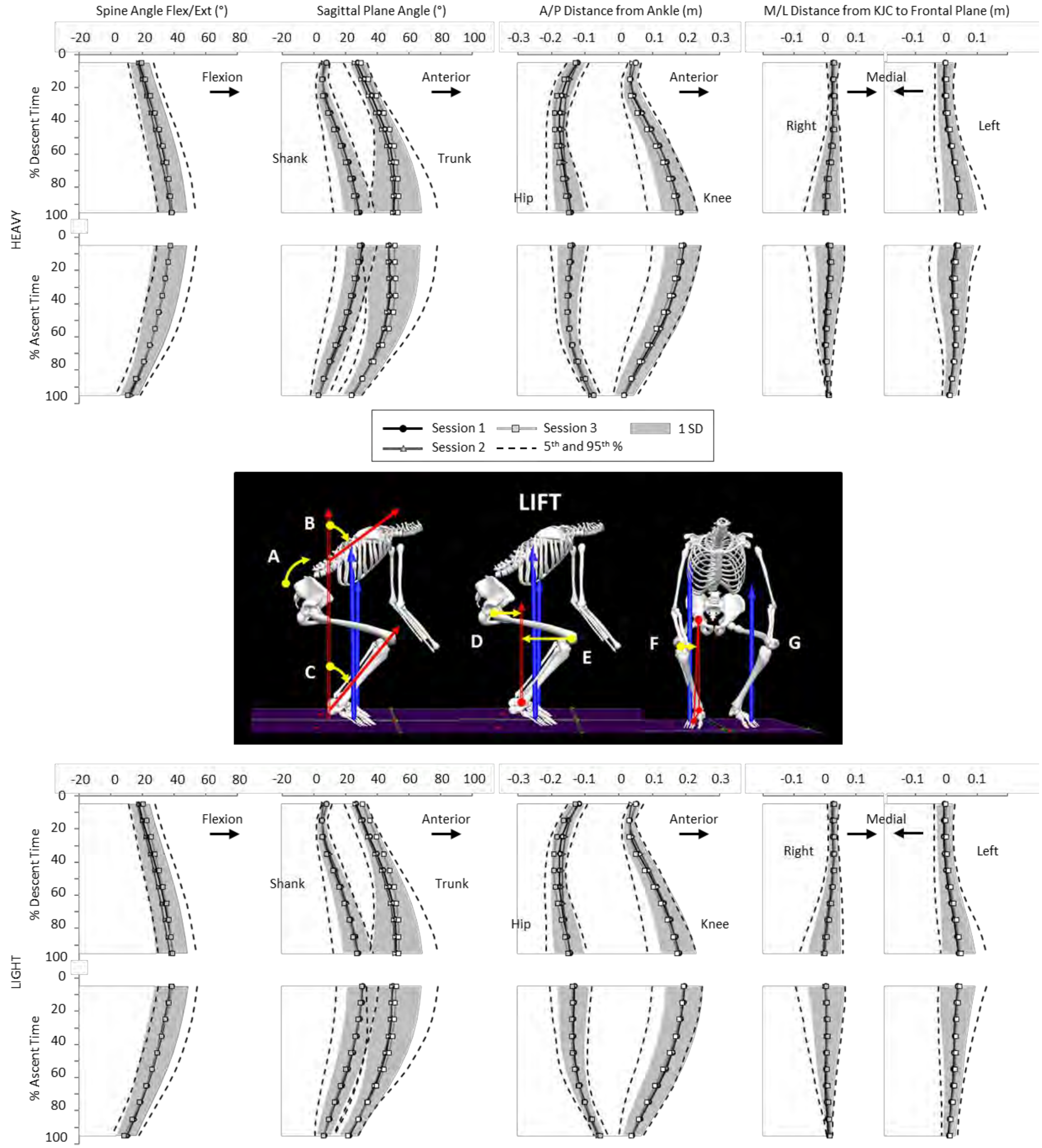


Figure A.1. The group's spine flexion/extension (A), trunk and shank angle (B and C), hip and knee to ankle distance (D and E), and right and left knee position (F and G) during the execution of the HEAVY (top) and LIGHT (bottom) lifting tasks. The data were normalized by time and expressed as a % of the descent and ascent phase separately. The dashed lines are used to describe the 5th and 95th percentile of each variable. The shaded area represents ± 1SD from the three-session average.

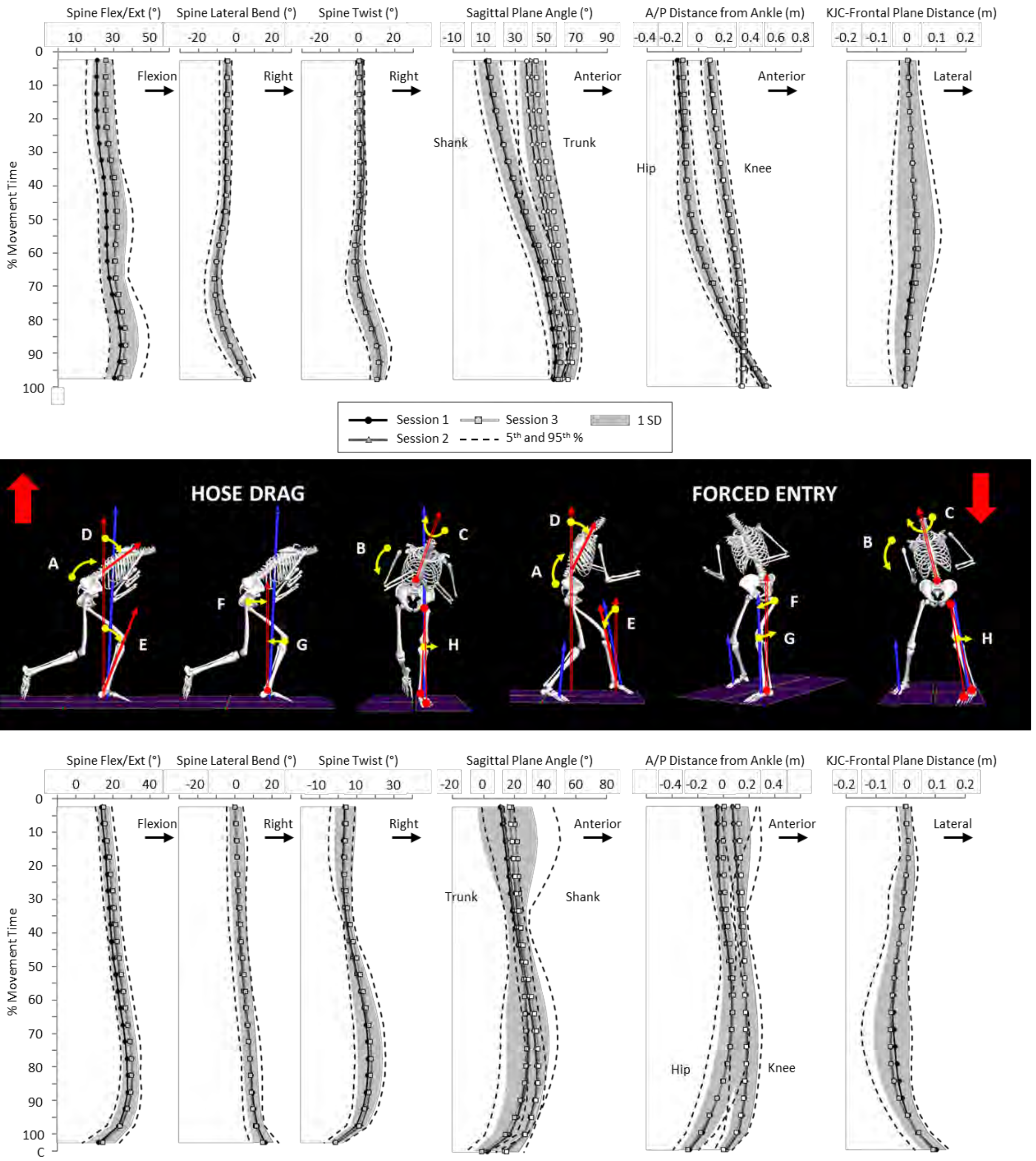


Figure A.2. The group's spine flexion/extension, lateral bend and twist (A, B and C), trunk and left shank angle (D and E), left hip and knee to ankle distance (F and G), and left knee position (H) during the execution of the simulated HOSE DRAG (top) and FORCED ENTRY (bottom) tasks. The group's data were expressed as a % of the total movement time. The last data point of the forced entry, which is marked by a 'C', depicts the moment that the sledgehammer made contact with the hanging object. The dashed lines are used to describe the 5th and 95th percentile of each variable. The shaded area represents ± 1SD from the three-session average.

A.1.2. Individual Differences

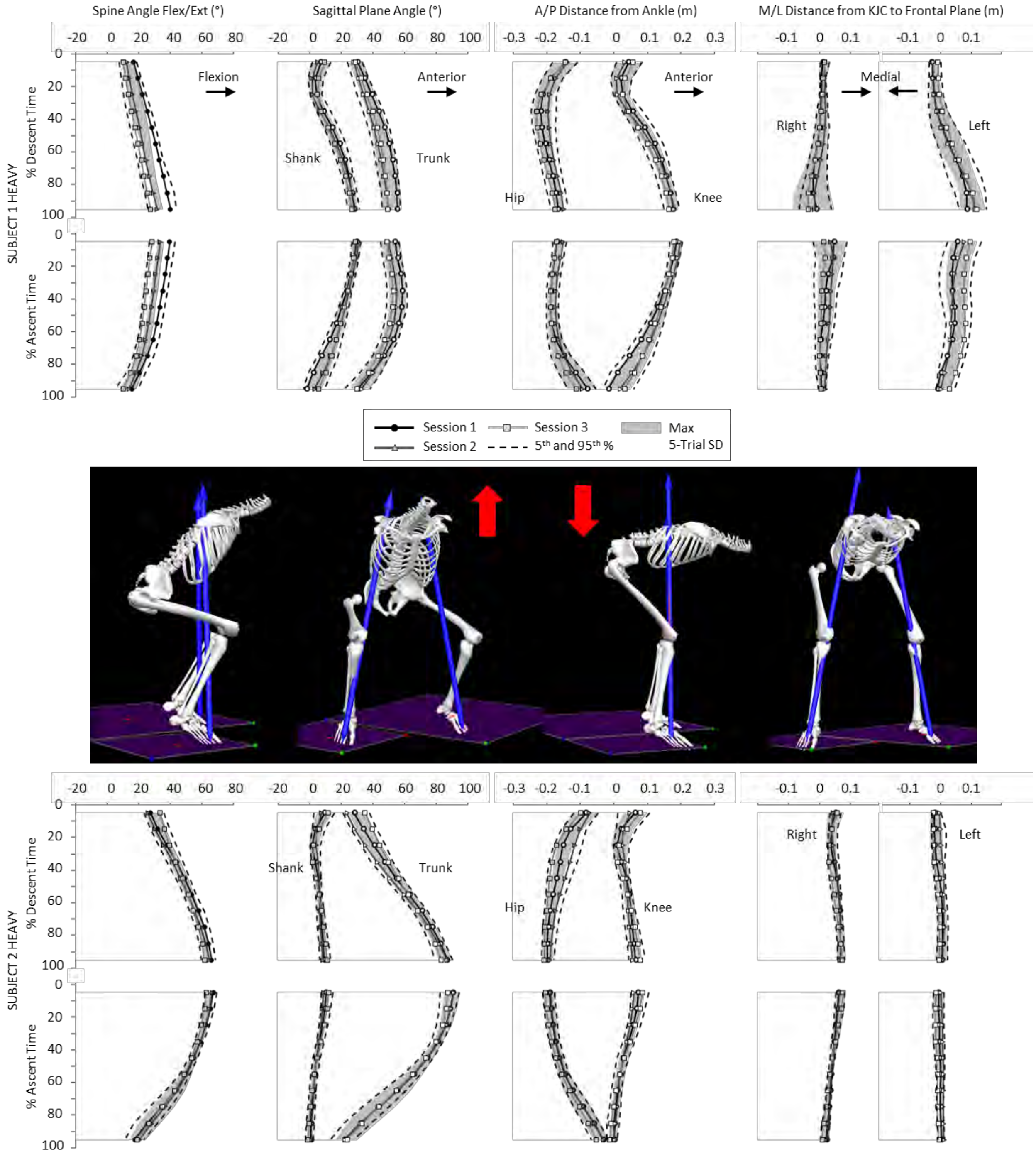


Figure A.3. This figure illustrates the mean spine flexion/extension, trunk and shank angle, hip and knee to ankle distance, and right and left knee position exhibited by two participants while they performed the HEAVY lifting task. The dashed lines describe the 5th and 95th percentile of each variable and the shaded area represents the maximum 5-trial (set) variation (standard deviation) observed during any session. Each participant's data were normalized by time and expressed as a % of the descent and ascent phase separately.

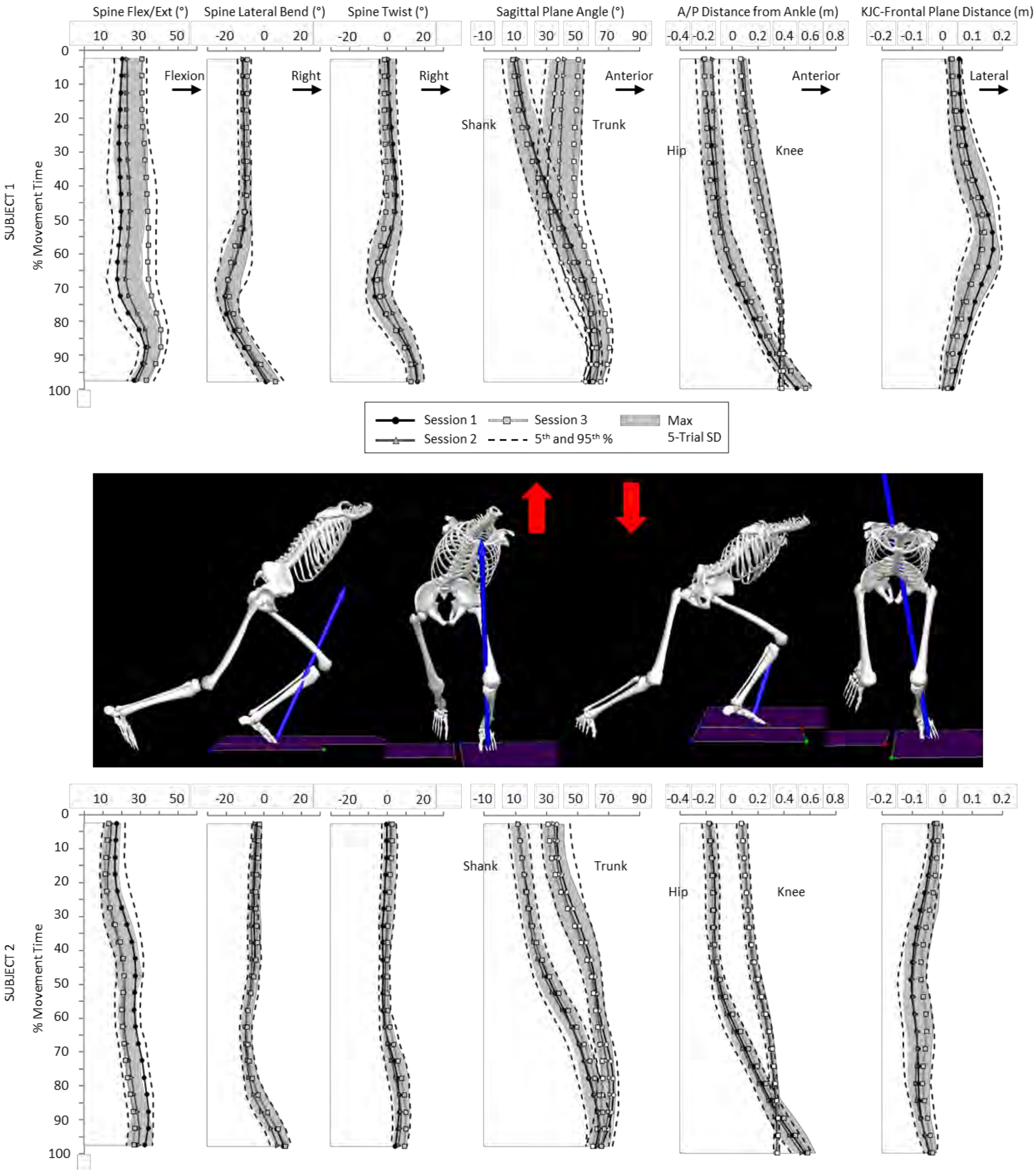


Figure A.4. This figure illustrates the mean spine flexion/extension, lateral bend and twist, trunk and left shank angle, left hip and knee to ankle distance, and left knee position exhibited by two participants while they performed the simulated HOSE DRAG task. The dashed lines describe the 5th and 95th percentile of each variable and the shaded area represents the maximum 5-trial (set) variation (standard deviation) observed during any session. Each participant's data were expressed as a % of the total movement time.

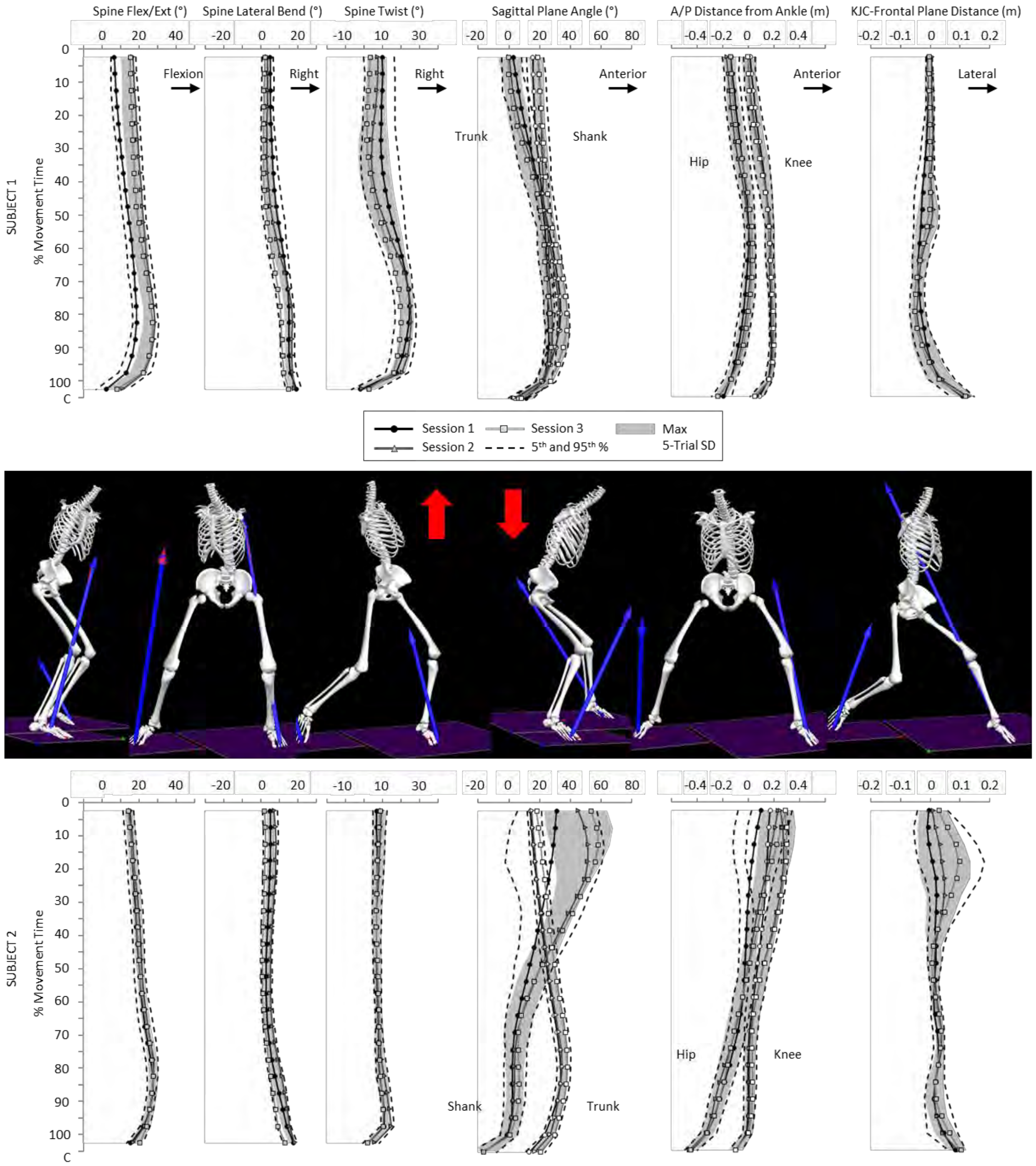


Figure A.5. This figure illustrates the mean spine flexion/extension, lateral bend and twist, trunk and left shank angle, left hip and knee to ankle distance, and left knee position exhibited by two participants while they performed the simulated FORCED ENTRY task. The dashed lines describe the 5th and 95th percentile of each variable and the shaded area represents the maximum 5-trial (set) variation (standard deviation) observed during any session. Each participant's data were expressed as a % of the total movement time. The last data point (C) depicts the moment of contact.

A.1.3. "Meaningful" Within-Subject Changes

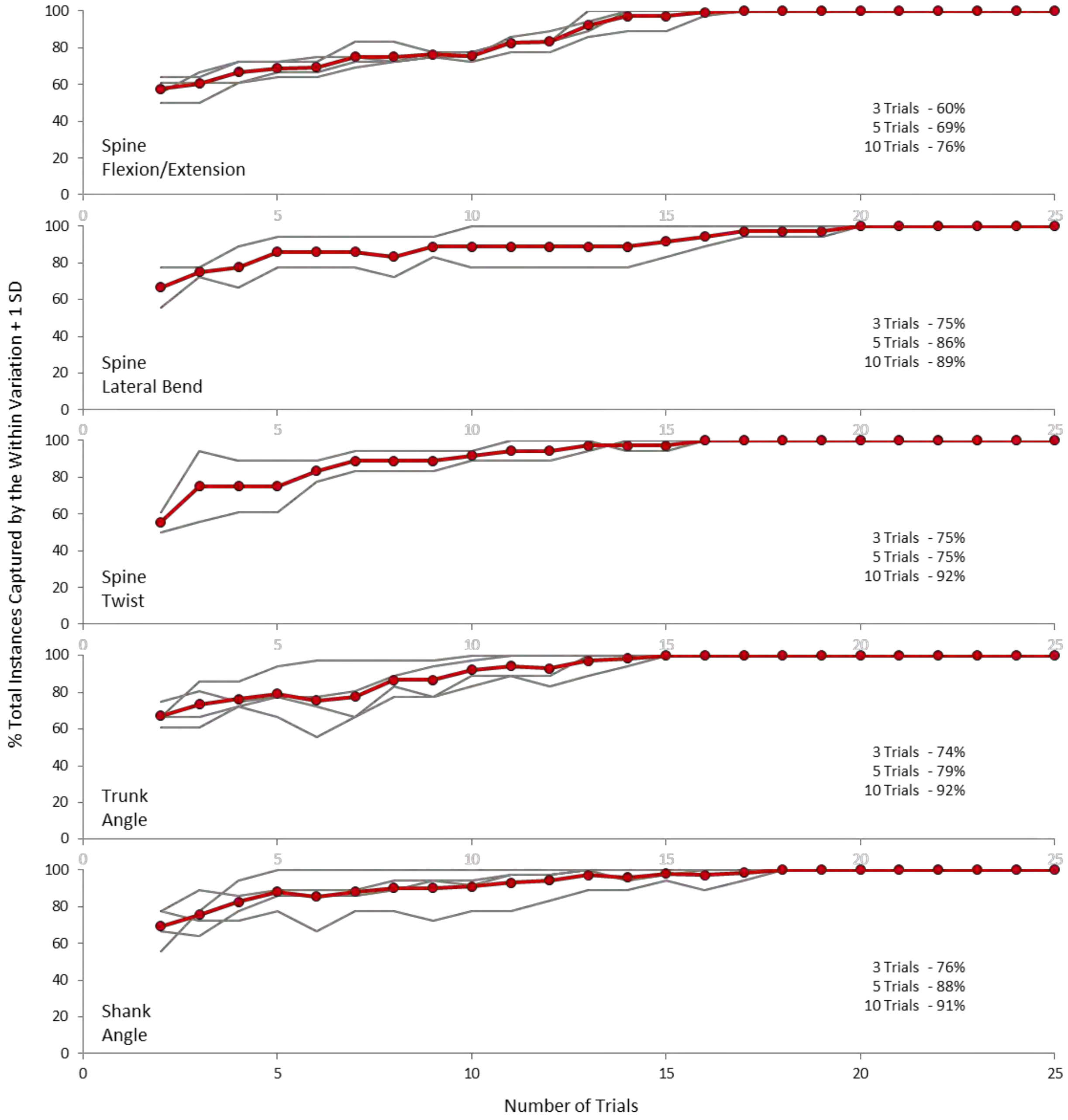


Figure A.6. The number of instances across all metrics (i.e. maximum, minimum and mean) and sessions (expressed as a % of the total number possible) whereby the sequential within-subject variation (+ 1SD) was larger than the 25-trial mean - sequential mean difference. The solid red lines represent the four-task mean, and the grey lines depict the results for each individual task. Data is presented for five of the variables used to describe participants' movement patterns. In each case, the success rate for three, five and ten trials is highlighted.

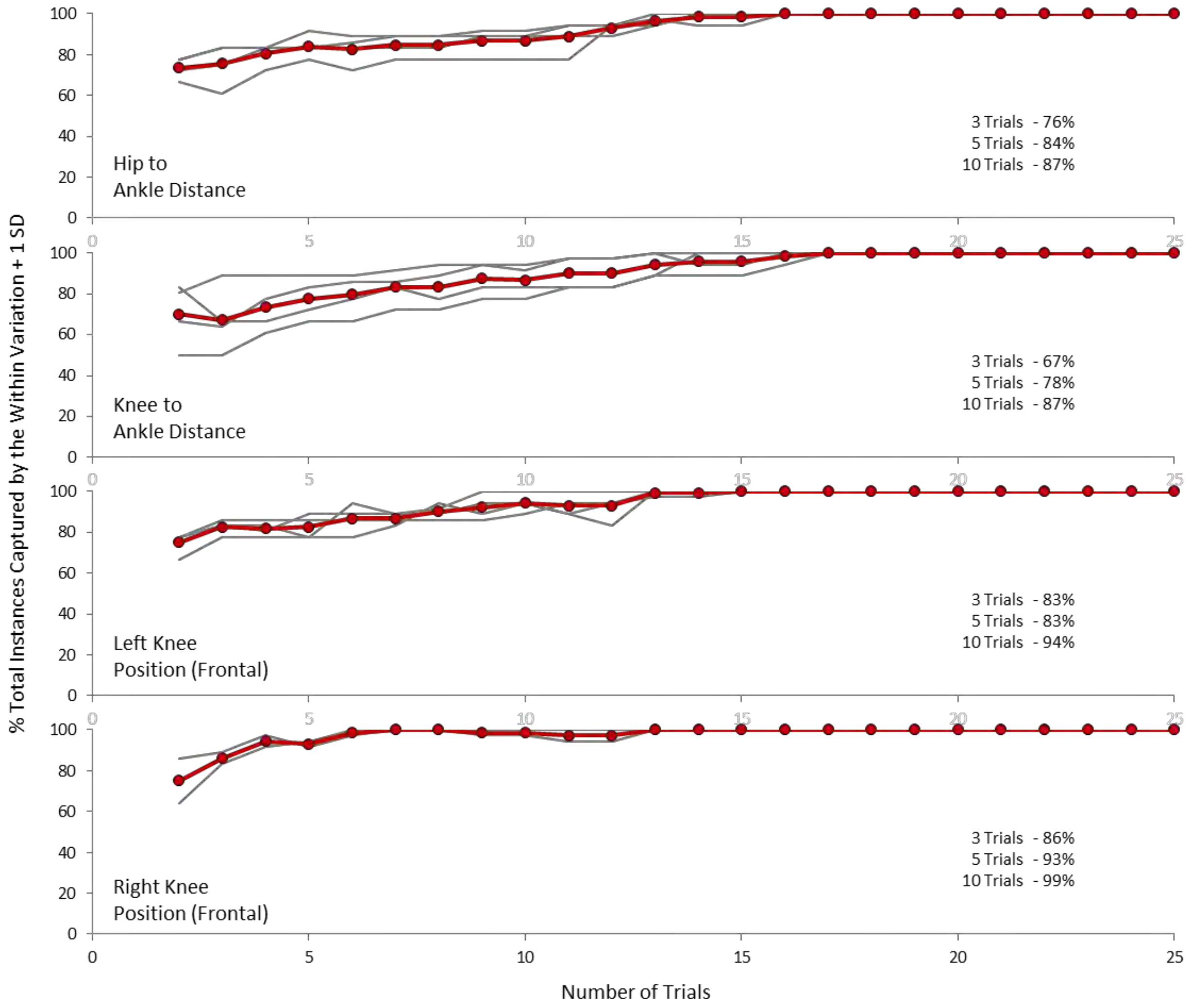


Figure A.7. The number of instances across all metrics (i.e. maximum, minimum and mean) and sessions (expressed as a % of the total number possible) whereby the sequential within-subject variation (+ 1SD) was larger than the 25-trial mean - sequential mean difference. The solid red lines represent the four-task mean, and the grey lines depict the results for each individual task. Data is presented for four of the variables used to describe participants' movement patterns. In each case, the success rate for three, five and ten trials is highlighted.

Appendix B

SUPPLEMENT - INVESTIGATION TWO

LOAD, SPEED AND THE EVALUATION OF MOVEMENT: A TASK'S DEMANDS INFLUENCE THE WAY WE MOVE

The peak and mean of each dependent variable used to describe participants' lift, squat, lunge, push and pull patterns are outlined in Tables B.1 – B.5, respectively. Data for each phase (e.g. descent and ascent) and condition (e.g. low load, low velocity) are presented, including significant main effects and load by speed interactions. Figures B.1 – B.8 illustrate each individual's time normalized data for each dependent measure used to characterize the lunge pattern. Although significant main effects of load and speed were seen when comparing the group's responses to each condition, substantial variation was seen amongst participants.

B.1.1. Group Behaviour

Table B.1. The peak (SD) and mean (SD) of each dependent variable used to describe participants' LIFT patterns. Data for each phase (i.e. descent and ascent) and condition (low load, low velocity – LLLV; low load, high velocity – LLHV; high load, low velocity – HLLV; and high load, high velocity – HLHV) are presented. Significant main effects and load x speed (L*S) interactions are described by p-values less than 0.05. N/A signifies that the main effects of load and speed were not reported because the interaction was significant.

LIFT		Spine Flex/Ext (°)	Trunk Angle (°)	Shank Angle (°)	Hip to Ankle Distance (cm)	Knee to Ankle Distance (cm)	Left Knee Position (cm)	Right Knee Position (cm)
PEAK Descent	LLLV	58.3 (10.4)	73.4 (15.9)	32.2 (10.0)	-18.8 (3.2)	22.1 (6.3)	-3.0 (5.0)	6.0 (5.1)
	LLHV	58.4 (9.5)	72.9 (15.6)	31.7 (8.6)	-19.5 (3.9)	21.6 (4.9)	-3.7 (6.0)	7.1 (5.7)
	HLLV	57.5 (10.2)	70.4 (14.7)	34.0 (8.9)	-19.0 (3.2)	22.9 (5.1)	-4.0 (5.4)	8.1 (6.9)
	HLHV	58.3 (9.7)	71.1 (14.5)	32.9 (8.0)	-19.5 (3.8)	22.3 (4.7)	-3.6 (5.1)	7.8 (7.3)
	Load	*0.360*	***0.007***	***0.038***	*0.734*	*0.058*	*0.271*	*N/A*
	Speed	*0.326*	*0.936*	*0.240*	***0.038***	***0.036***	*0.623*	*N/A*
	L*S	*0.316*	*0.366*	*0.584*	*0.631*	*0.174*	*0.053*	***0.046***
MEAN Descent	LLLV	44.1 (8.8)	57.3 (11.0)	18.0 (7.4)	-15.6 (3.3)	12.7 (5.1)	0.5 (4.0)	2.0 (3.1)
	LLHV	42.6 (8.3)	55.8 (11.3)	17.4 (6.4)	-15.9 (3.9)	12.4 (4.2)	0.4 (3.8)	2.2 (3.2)
	HLLV	44.2 (9.1)	56.7 (10.5)	19.3 (6.7)	-15.8 (3.1)	13.6 (4.4)	0.6 (4.3)	2.1 (3.5)
	HLHV	43.1 (8.3)	55.8 (9.7)	18.6 (6.0)	-15.9 (3.4)	13.2 (4.0)	0.9 (4.2)	1.9 (4.0)
	Load	*0.643*	*0.665*	***0.008***	*0.781*	***0.008***	*0.148*	*0.596*
	Speed	***0.029***	*0.111*	*0.102*	*0.577*	*0.208*	*0.458*	*0.975*
	L*S	*0.513*	*0.553*	*0.919*	*0.789*	*0.766*	*0.284*	*0.244*
PEAK Ascent	LLLV	58.1 (10.7)	70.5 (16.6)	32.0 (10.3)	-18.0 (2.8)	22.0 (6.6)	-3.6 (5.3)	6.6 (5.3)
	LLHV	58.3 (9.6)	70.8 (16.0)	31.7 (8.8)	-18.3 (2.8)	21.6 (5.1)	-4.6 (6.2)	8.3 (6.1)
	HLLV	56.9 (10.5)	67.6 (15.4)	33.6 (8.7)	-20.2 (2.9)	22.7 (5.1)	-5.0 (5.8)	9.2 (7.3)
	HLHV	57.8 (9.8)	68.7 (15.4)	32.7 (7.9)	-19.9 (3.2)	22.1 (4.7)	-4.6 (6.1)	9.3 (7.8)
	Load	*0.090*	***0.015***	*0.067*	*N/A*	*0.163*	*N/A*	*N/A*
	Speed	*0.233*	*0.432*	*0.351*	*N/A*	*0.270*	*N/A*	*N/A*
	L*S	*0.389*	*0.598*	*0.563*	***0.036***	*0.738*	***0.011***	***0.029***
MEAN Ascent	LLLV	42.7 (8.8)	54.3 (10.6)	20.7 (7.6)	-14.1 (2.4)	14.5 (5.2)	-0.1 (4.6)	3.0 (3.4)
	LLHV	42.6 (8.5)	55.8 (11.4)	20.6 (6.9)	-14.5 (2.6)	14.5 (4.4)	-0.5 (4.9)	3.5 (3.9)
	HLLV	42.7 (9.3)	54.7 (10.6)	17.5 (6.3)	-16.5 (2.4)	12.3 (4.2)	0.0 (5.0)	3.1 (4.2)
	HLHV	42.6 (8.9)	56.3 (11.2)	17.4 (6.7)	-16.4 (2.7)	12.3 (4.5)	0.7 (5.6)	2.8 (4.8)
	Load	*0.992*	*0.547*	***< 0.000***	***< 0.000***	***< 0.000***	*N/A*	*0.285*
	Speed	*0.832*	***0.029***	*0.774*	*0.207*	*0.861*	*N/A*	*0.727*
	L*S	*0.784*	*0.919*	*0.926*	*0.086*	*0.911*	***0.013***	*0.088*

Table B.2. The peak (SD) and mean (SD) of each dependent variable used to describe participants' SQUAT patterns. Data for each phase (i.e. descent and ascent) and condition (low load, low velocity – LLLV; low load, high velocity – LLHV; high load, low velocity – HLLV; and high load, high velocity – HLHV) are presented. Significant main effects and load x speed (L*S) interactions are described by p-values less than 0.05. N/A signifies that the main effects of load and speed were not reported because the interaction was significant.

SQUAT		Spine Flex/Ext (°)	Trunk Angle (°)	Shank Angle (°)	Hip to Ankle Distance (cm)	Knee to Ankle Distance (cm)	Left Knee Position (cm)	Right Knee Position (cm)
PEAK Descent	LLLV	51.7 (14.6)	52.4 (12.6)	39.6 (7.2)	-16.8 (4.1)	26.7 (4.1)	-3.6 (4.5)	8.1 (6.9)
	LLHV	50.9 (13.6)	52.9 (11.2)	36.8 (6.0)	-17.9 (3.4)	25.1 (3.7)	-4.2 (6.1)	8.4 (7.1)
	HLLV	47.0 (13.3)	50.9 (11.2)	40.1 (7.2)	-15.7 (3.8)	26.9 (4.3)	-3.6 (4.8)	8.4 (7.2)
	HLHV	49.0 (12.2)	53.0 (9.4)	36.8 (5.8)	-17.1 (3.4)	25.1 (3.7)	-4.4 (6.2)	8.4 (7.4)
	Load	*N/A*	*0.307*	*0.613*	***< 0.000***	*0.747*	*0.665*	*0.712*
	Speed	*N/A*	*0.094*	***< 0.000***	***< 0.000***	***< 0.000***	*0.098*	*0.754*
	L*S	***0.028***	*0.094*	*0.412*	*0.414*	*0.431*	*0.669*	*0.581*
MEAN Descent	LLLV	30.2 (9.6)	37.7 (9.7)	29.2 (4.7)	-12.6 (3.9)	20.4 (2.9)	1.7 (4.9)	2.2 (4.9)
	LLHV	26.5 (8.5)	35.7 (8.2)	26.6 (3.4)	-12.6 (2.9)	18.9 (2.3)	0.7 (4.4)	3.0 (4.3)
	HLLV	27.3 (8.7)	36.8 (8.7)	29.1 (4.4)	-11.6 (3.5)	20.4 (3.0)	1.3 (4.6)	2.4 (4.4)
	HLHV	26.1 (8.2)	35.5 (7.4)	27.3 (3.6)	-11.9 (3.0)	19.3 (2.5)	0.9 (4.8)	2.5 (4.6)
	Load	*N/A*	*0.296*	*0.312*	***< 0.000***	*0.277*	*0.762*	*N/A*
	Speed	*N/A*	***0.004***	***< 0.000***	*0.467*	***< 0.000***	***0.018***	*N/A*
	L*S	***0.001***	*0.241*	*0.091*	*0.423*	*0.100*	*0.223*	***0.040***
PEAK Ascent	LLLV	52.0 (14.6)	53.1 (12.1)	39.2 (7.3)	-17.5 (4.1)	26.4 (4.2)	-4.2 (4.9)	8.6 (7.1)
	LLHV	51.2 (13.8)	52.4 (10.8)	37.6 (5.9)	-17.4 (3.2)	25.7 (3.6)	-4.8 (6.5)	9.1 (7.1)
	HLLV	47.2 (13.3)	51.1 (10.9)	40.0 (7.2)	-16.2 (3.7)	26.9 (4.4)	-4.4 (5.6)	9.0 (9.0)
	HLHV	49.2 (12.3)	52.7 (9.1)	37.5 (5.8)	-17.0 (3.3)	25.5 (3.7)	-5.1 (6.3)	9.3 (7.5)
	Load	*N/A*	*N/A*	*0.503*	*N/A*	*0.582*	*0.470*	*0.500*
	Speed	*N/A*	*N/A*	***< 0.000***	*N/A*	***< 0.000***	*0.056*	*0.279*
	L*S	***0.030***	***0.019***	*0.141*	***0.029***	*0.108*	*0.856*	*0.721*
MEAN Ascent	LLLV	37.1 (12.4)	42.8 (10.8)	28.6 (5.5)	-14.3 (4.0)	19.9 (3.5)	0.6 (6.0)	3.7 (6.2)
	LLHV	33.0 (10.2)	39.4 (9.5)	28.4 (4.6)	-13.6 (3.2)	19.9 (3.1)	-0.5 (6.1)	4.4 (5.3)
	HLLV	32.9 (10.8)	41.0 (9.3)	29.3 (5.6)	-13.5 (3.6)	20.4 (3.7)	0.1 (5.6)	4.1 (5.6)
	HLHV	32.3 (10.2)	39.7 (8.7)	28.7 (4.7)	-13.3 (3.3)	20.2 (3.3)	-0.2 (6.0)	4.2 (5.5)
	Load	*N/A*	*N/A*	*0.164*	***0.048***	*0.140*	*0.860*	*0.832*
	Speed	*N/A*	*N/A*	*0.310*	*0.063*	*0.543*	*0.063*	*0.257*
	L*S	***0.001***	***0.016***	*0.540*	*0.141*	*0.489*	*0.166*	*0.208*

Table B.3. The peak (SD) and mean (SD) of each dependent variable used to describe participants' LUNGE patterns. Data for each phase (i.e. descent and ascent) and condition (low load, low velocity – LLLV; low load, high velocity – LLHV; high load, low velocity – HLLV; and high load, high velocity – HLHV) are presented (right side only for lower limb variables). The peak spine lateral bend and twist represent the range (maximum – minimum) of motion exhibited during the corresponding phase. Significant main effects and load x speed (L*S) interactions are described by p-values less than 0.05. N/A signifies that the main effects of load and speed were not reported because the interaction was significant.

LUNGE		Spine Flex/Ext (°)	Spine Lateral Bend (°)	Spine Twist (°)	Trunk Angle (°)	Shank Angle (°)	Hip to Ankle Distance (cm)	Knee to Ankle Distance (cm)	Knee Position (cm)
PEAK Descent	LLLV	22.3 (10.7)	9.2 (3.1)	6.7 (2.4)	20.4 (8.4)	32.3 (4.0)	-46.4 (4.5)	22.6 (2.5)	12.8 (7.1)
	LLHV	31.7 (12.1)	10.9 (4.3)	7.1 (1.9)	26.5 (10.9)	34.8 (4.3)	-48.8 (4.3)	24.3 (2.8)	13.5 (7.5)
	HLLV	25.2 (12.5)	9.2 (3.6)	6.0 (2.0)	23.5 (9.8)	33.9 (4.2)	-46.9 (3.7)	23.7 (2.7)	11.9 (6.5)
	HLHV	35.3 (10.5)	11.0 (4.0)	6.8 (2.3)	31.3 (10.6)	36.2 (4.4)	-48.4 (4.4)	25.1 (2.9)	12.9 (7.4)
	Load	***< 0.000***	*0.919*	***0.022***	***< 0.000***	***0.001***	*0.784*	***0.001***	***0.025***
	Speed	***< 0.000***	***< 0.000***	***0.022***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	*0.070*
	L*S	*0.628*	*0.627*	*0.294*	*0.139*	*0.884*	*0.104*	*0.627*	*0.556*
MEAN Descent	LLLV	12.6 (7.3)	0.9 (2.8)	3.2 (2.4)	10.6 (5.4)	4.5 (4.4)	-33.4 (3.5)	3.2 (3.2)	3.3 (3.6)
	LLHV	14.9 (7.0)	0.7 (2.6)	2.7 (2.6)	13.6 (7.0)	2.7 (3.9)	-34.5 (3.3)	1.9 (2.9)	3.0 (3.3)
	HLLV	14.6 (6.5)	0.1 (2.7)	2.5 (3.5)	12.9 (6.2)	2.8 (3.3)	-34.4 (2.9)	2.1 (2.4)	2.7 (3.1)
	HLHV	18.2 (7.1)	0.2 (2.9)	2.4 (3.4)	17.1 (7.2)	3.2 (4.3)	-34.8 (3.4)	2.2 (3.1)	3.1 (3.6)
	Load	***< 0.000***	***0.011***	*0.106*	***< 0.000***	*N/A*	*N/A*	*N/A*	*N/A*
	Speed	***< 0.000***	*0.969*	*0.158*	***< 0.000***	*N/A*	*N/A*	*N/A*	*N/A*
	L*S	*0.107*	*0.329*	*0.288*	*0.074*	***< 0.000***	***0.041***	***0.001***	***0.043***
PEAK Ascent	LLLV	22.6 (11.0)	7.7 (4.0)	6.0 (2.2)	20.8 (6.5)	34.1 (6.5)	-46.1 (4.0)	23.7 (3.7)	13.0 (7.3)
	LLHV	31.9 (11.8)	8.4 (3.3)	6.8 (2.5)	27.1 (6.1)	32.8 (6.1)	-49.5 (5.0)	22.9 (3.7)	13.5 (7.6)
	HLLV	25.6 (10.4)	8.0 (3.4)	5.6 (2.0)	24.2 (5.2)	32.8 (5.2)	-46.5 (3.7)	23.1 (3.3)	12.0 (7.1)
	HLHV	35.2 (10.3)	8.9 (3.4)	7.2 (2.5)	31.9 (6.7)	34.1 (6.7)	-49.2 (5.1)	23.8 (4.4)	12.7 (7.6)
	Load	***< 0.000***	*0.394*	*0.956*	***< 0.000***	*N/A*	*0.941*	*N/A*	***0.016***
	Speed	***< 0.000***	***0.024***	***0.001***	***< 0.000***	*N/A*	***< 0.000***	*N/A*	*0.250*
	L*S	*0.824*	*0.676*	*0.068*	*0.204*	***0.015***	*0.151*	***0.013***	*0.802*
MEAN Ascent	LLLV	14.8 (8.2)	1.8 (2.9)	3.4 (2.6)	13.6 (6.2)	7.5 (4.0)	-31.4 (3.1)	5.3 (2.8)	5.2 (4.3)
	LLHV	18.7 (8.8)	3.0 (3.0)	3.0 (3.3)	16.9 (8.4)	0.9 (4.3)	-35.9 (4.1)	0.7 (3.1)	5.1 (4.4)
	HLLV	16.4 (6.9)	1.7 (3.0)	2.7 (3.7)	15.6 (6.5)	4.8 (4.0)	-33.0 (2.9)	3.5 (2.9)	4.5 (4.3)
	HLHV	20.3 (7.8)	2.5 (2.6)	2.8 (3.3)	19.5 (7.8)	0.1 (4.4)	-36.2 (4.3)	0.1 (3.2)	4.5 (4.6)
	Load	***0.009***	*0.319*	***0.039***	***< 0.000***	*N/A*	*N/A*	*N/A*	***0.006***
	Speed	***< 0.000***	***< 0.000***	*0.522*	***< 0.000***	*N/A*	*N/A*	*N/A*	*0.815*
	L*S	*0.980*	*0.442*	*0.194*	*0.421*	***< 0.000***	***0.002***	***< 0.000***	*0.873*

Table B.4. The peak (SD) and mean (SD) of each dependent variable used to describe participants' PUSH patterns. Data for each phase (i.e. away and towards) and condition (low load, low velocity – LLLV; low load, high velocity – LLHV; high load, low velocity – HLLV; and high load, high velocity – HLHV) are presented (left side only for lower limb variables). The peak spine lateral bend and twist represent the range (maximum – minimum) of motion exhibited during the corresponding phase. Significant main effects and load x speed (L*S) interactions are described by p-values less than 0.05. N/A signifies that the main effects of load and speed were not reported because the interaction was significant.

PUSH		Spine Flex/Ext (°)	Spine Lateral Bend (°)	Spine Twist (°)	Trunk Angle (°)	Shank Angle (°)	Hip to Ankle Distance (cm)	Knee to Ankle Distance (cm)	Knee Position (cm)
PEAK Away from Body	LLLV	4.9 (2.1)	7.2 (4.0)	22.2 (7.0)	19.4 (9.0)	1.4 (9.1)	-30.1 (4.2)	0.9 (6.7)	0.1 (2.9)
	LLHV	9.3 (3.9)	10.9 (6.0)	32.0 (7.1)	19.4 (8.9)	6.3 (7.0)	-30.8 (4.8)	4.7 (5.2)	-0.9 (3.4)
	HLLV	6.1 (2.9)	9.6 (4.6)	25.7 (6.8)	21.1 (8.4)	5.0 (7.8)	-30.1 (5.2)	3.7 (5.8)	0.6 (3.3)
	HLHV	12.3 (5.6)	13.5 (6.8)	32.4 (6.7)	21.7 (9.3)	9.6 (7.1)	-30.9 (5.1)	6.9 (5.2)	-1.0 (4.0)
	Load	***< 0.000***	***< 0.000***	*N/A*	***0.001***	***< 0.000***	*0.805*	***< 0.000***	*N/A*
	Speed	***< 0.000***	***< 0.000***	*N/A*	*0.551*	***< 0.000***	*0.080*	***< 0.000***	*N/A*
	L*S	***0.012***	*0.718*	***< 0.000***	*0.392*	*0.712*	*0.951*	*0.467*	***0.023***
MEAN Away from Body	LLLV	3.5 (6.7)	-1.1 (3.8)	-8.0 (4.4)	15.1 (8.4)	-0.4 (8.9)	-28.4 (4.3)	-0.4 (6.5)	1.1 (2.9)
	LLHV	1.9 (7.0)	-0.6 (3.7)	-9.2 (5.1)	14.6 (8.2)	3.5 (7.1)	-28.0 (4.8)	2.6 (5.3)	1.3 (3.3)
	HLLV	2.3 (6.6)	-0.5 (3.8)	-5.5 (4.8)	17.2 (7.9)	2.9 (7.6)	-27.8 (5.2)	2.1 (5.8)	2.1 (3.4)
	HLHV	1.4 (6.8)	-1.7 (4.5)	-7.3 (5.0)	17.8 (8.6)	6.0 (7.2)	-27.1 (5.4)	4.3 (5.4)	1.7 (3.8)
	Load	***0.022***	*N/A*	***< 0.000***	***< 0.000***	***< 0.000***	*0.065*	***< 0.000***	*N/A*
	Speed	***0.003***	*N/A*	***< 0.000***	*0.891*	***< 0.000***	*0.166*	***< 0.000***	*N/A*
	L*S	*0.299*	***0.001***	*0.303*	*0.095*	*0.394*	*0.595*	*0.265*	***0.015***
PEAK Towards Body	LLLV	4.7 (2.1)	4.6 (3.0)	16.8 (5.9)	19.5 (9.2)	-0.1 (9.1)	-30.2 (4.1)	-0.1 (6.6)	0.4 (2.8)
	LLHV	6.3 (3.4)	6.8 (4.0)	22.4 (6.2)	19.7 (9.2)	3.0 (7.5)	-30.7 (4.4)	2.2 (5.6)	0.5 (3.2)
	HLLV	4.7 (1.7)	5.7 (3.2)	18.7 (5.6)	20.8 (9.2)	2.7 (7.4)	-30.5 (4.8)	2.0 (5.6)	1.0 (3.2)
	HLHV	6.0 (2.6)	8.3 (4.9)	24.4 (6.6)	21.7 (9.9)	4.4 (7.2)	-31.5 (4.7)	3.1 (5.3)	1.1 (3.6)
	Load	*0.488*	***< 0.000***	***< 0.000***	***0.005***	***0.001***	*0.099*	***0.001***	***< 0.000***
	Speed	***< 0.000***	***< 0.000***	***< 0.000***	*0.316*	***0.002***	*0.059*	***0.001***	*0.757*
	L*S	*0.469*	*0.438*	*0.797*	*0.315*	*0.163*	*0.604*	*0.092*	*0.915*
MEAN Towards Body	LLLV	4.2 (6.9)	-3.6 (4.6)	-12.3 (4.7)	15.7 (8.4)	-1.6 (8.7)	-28.8 (4.2)	-1.2 (6.4)	1.3 (2.8)
	LLHV	4.3 (7.1)	-4.6 (5.1)	-15.6 (5.4)	16.7 (9.0)	1.3 (7.4)	-29.1 (4.5)	1.0 (5.6)	2.4 (3.4)
	HLLV	2.1 (6.8)	-4.2 (4.5)	-10.5 (4.9)	16.9 (8.4)	1.0 (7.3)	-29.0 (4.8)	0.8 (5.5)	2.5 (3.2)
	HLHV	2.4 (7.0)	-6.2 (5.6)	-12.7 (5.7)	18.4 (9.0)	2.2 (7.1)	-29.6 (4.7)	1.6 (5.3)	3.3 (3.6)
	Load	***< 0.000***	***0.002***	*N/A*	***0.007***	***0.003***	*0.304*	***0.002***	***< 0.000***
	Speed	*0.484*	***< 0.000***	*N/A*	***0.020***	***0.003***	*0.290*	***0.002***	***< 0.000***
	L*S	*0.756*	*0.070*	***0.046***	*0.357*	*0.102*	*0.624*	*0.056*	*0.155*

Table B.5. The peak (SD) and mean (SD) of each dependent variable used to describe participants' PULL patterns. Data for each phase (i.e. towards and away) and condition (low load, low velocity – LLLV; low load, high velocity – LLHV; high load, low velocity – HLLV; and high load, high velocity – HLHV) are presented (left side only for lower limb variables). The peak spine lateral bend and twist represent the range (maximum – minimum) of motion exhibited during the corresponding phase. Significant main effects and load x speed (L*S) interactions are described by p-values less than 0.05. N/A signifies that the main effects of load and speed were not reported because the interaction was significant.

PULL		Spine Flex/Ext (°)	Spine Lateral Bend (°)	Spine Twist (°)	Trunk Angle (°)	Shank Angle (°)	Hip to Ankle Distance (cm)	Knee to Ankle Distance (cm)	Knee Position (cm)
PEAK Towards Body	LLLV	8.8 (4.1)	4.6 (2.5)	25.8 (7.6)	17.7 (10.1)	-7.8 (5.8)	-32.7 (6.0)	-5.7 (4.2)	0.0 (2.2)
	LLHV	10.0 (4.2)	6.2 (2.9)	36.3 (7.9)	22.5 (9.3)	-2.1 (6.9)	-36.1 (6.2)	-1.5 (5.1)	-1.6 (3.0)
	HLLV	8.8 (4.7)	5.9 (2.8)	31.3 (8.3)	21.2 (9.7)	-8.6 (5.2)	-37.2 (6.2)	-6.2 (3.9)	-0.4 (3.0)
	HLHV	11.3 (5.2)	6.8 (3.0)	38.7 (8.8)	24.2 (10.5)	-2.7 (7.5)	-39.9 (5.2)	-1.8 (5.4)	-2.3 (2.9)
	Load	*0.170*	***< 0.000***	*N/A*	***< 0.000***	*0.200*	***< 0.000***	*0.274*	***0.008***
	Speed	***0.001***	***0.006***	*N/A*	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***
	L*S	*0.083*	*0.072*	***0.001***	*0.184*	*0.784*	*0.186*	*0.822*	*0.380*
MEAN Towards Body	LLLV	10.0 (9.4)	-0.9 (3.7)	-10.3 (5.0)	10.7 (10.1)	-9.6 (5.7)	-30.9 (6.0)	-7.0 (4.1)	0.8 (2.3)
	LLHV	14.0 (8.0)	-3.7 (4.3)	-10.6 (5.7)	15.7 (9.0)	-7.0 (5.4)	-31.4 (6.4)	-5.1 (4.0)	0.5 (2.5)
	HLLV	13.5 (9.1)	-1.7 (3.9)	-11.9 (5.6)	12.8 (9.9)	-11.2 (5.3)	-34.6 (6.5)	-8.1 (3.9)	1.1 (2.9)
	HLHV	16.8 (8.9)	-5.5 (5.0)	-11.2 (5.2)	15.8 (10.0)	-8.2 (5.8)	-33.6 (5.9)	-5.9 (4.2)	0.6 (2.8)
	Load	***< 0.000***	*N/A*	***0.008***	*0.103*	***0.004***	*N/A*	***0.005***	*0.232*
	Speed	***< 0.000***	*N/A*	*0.716*	***< 0.000***	***< 0.000***	*N/A*	***< 0.000***	***0.018***
	L*S	*0.406*	***0.044***	*0.090*	***0.039***	*0.716*	***0.019***	*0.732*	*0.476*
PEAK Away from Body	LLLV	5.5 (2.9)	4.2 (2.1)	23.2 (7.4)	13.6 (9.7)	-8.2 (5.8)	-31.9 (5.8)	-6.0 (4.2)	0.1 (2.2)
	LLHV	7.3 (3.8)	6.5 (3.3)	33.3 (9.3)	18.2 (9.4)	-2.3 (7.2)	-33.0 (6.7)	-1.6 (5.2)	-1.5 (3.0)
	HLLV	5.7 (2.7)	5.5 (2.5)	28.5 (9.3)	16.8 (9.6)	-8.4 (5.3)	-35.2 (6.3)	-6.1 (3.9)	-0.4 (3.1)
	HLHV	7.0 (3.7)	6.3 (2.8)	34.1 (9.5)	19.1 (9.8)	-3.1 (7.5)	-34.6 (6.4)	-2.2 (5.4)	-1.8 (3.0)
	Load	*0.974*	*N/A*	*N/A*	*N/A*	*0.281*	*N/A*	*0.383*	*0.051*
	Speed	***< 0.000***	*N/A*	*N/A*	*N/A*	***< 0.000***	*N/A*	***< 0.000***	***< 0.000***
	L*S	*0.322*	***0.008***	***< 0.000***	***0.011***	*0.495*	***0.007***	*0.453*	*0.431*
MEAN Away from Body	LLLV	8.1 (9.2)	-0.5 (3.7)	-5.8 (5.5)	8.6 (9.8)	-10.3 (5.4)	-30.4 (5.9)	-7.5 (3.9)	0.8 (2.2)
	LLHV	10.7 (8.5)	-2.9 (3.9)	-3.1 (5.4)	12.0 (8.8)	-6.4 (6.6)	-29.3 (7.1)	-4.6 (4.9)	0.3 (2.7)
	HLLV	11.9 (8.8)	-1.4 (4.2)	-7.0 (6.1)	10.8 (9.8)	-11.1 (5.4)	-32.6 (6.7)	-8.0 (3.9)	0.7 (3.0)
	HLHV	13.8 (9.0)	-4.4 (4.5)	-4.8 (5.9)	13.3 (9.8)	-7.5 (6.4)	-30.1 (7.2)	-5.4 (4.6)	0.2 (2.9)
	Load	***< 0.000***	***< 0.000***	***0.003***	***0.005***	*0.057*	*N/A*	*0.084*	*0.723*
	Speed	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	***< 0.000***	*N/A*	***< 0.000***	***0.001***
	L*S	*0.321*	*0.174*	*0.309*	*0.258*	*0.683*	***0.038***	*0.621*	*0.682*

B.1.2. Individual Differences

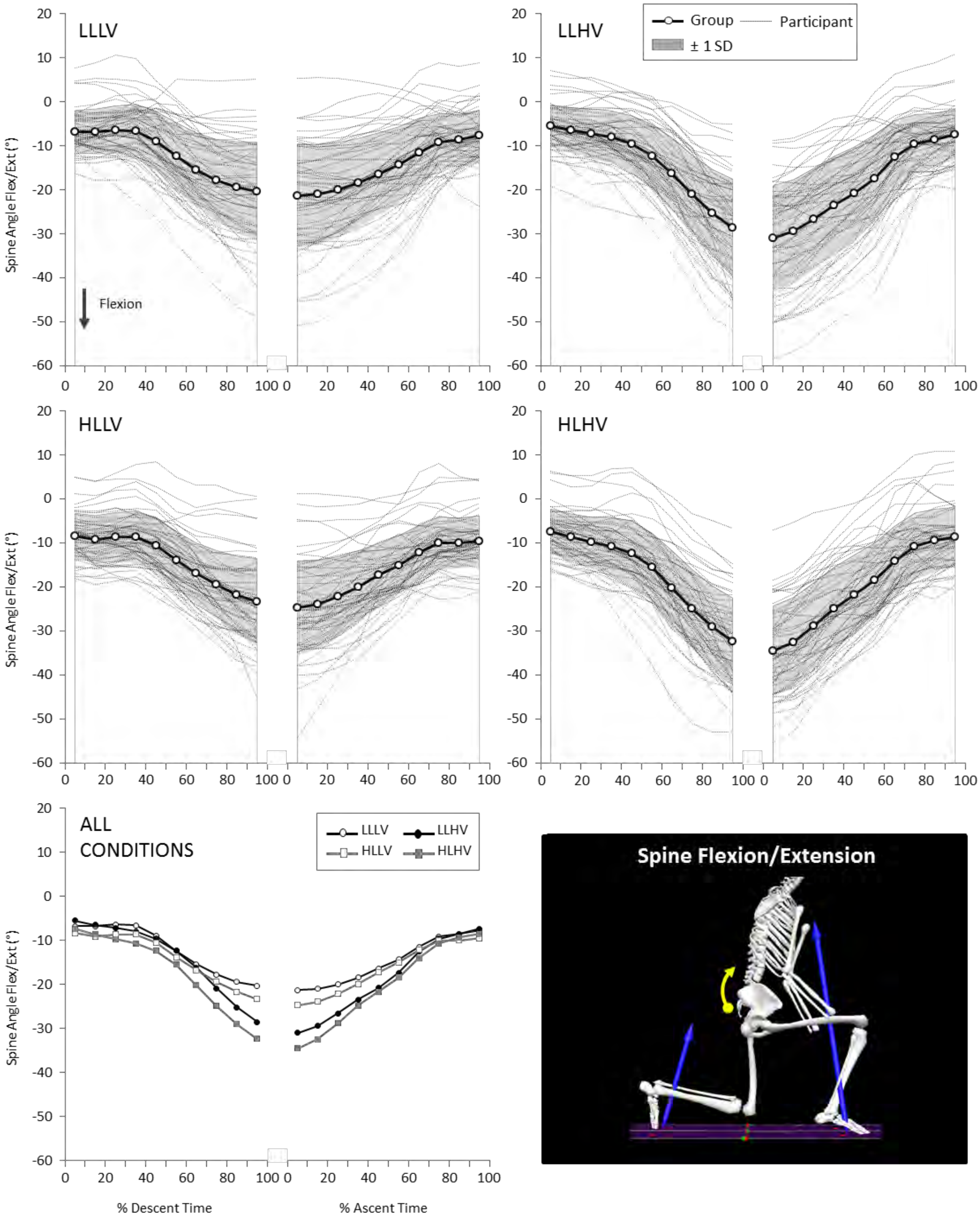


Figure B.1. The spine flexion/extension exhibited by the group and all participants while LUNGING with each of the four load/movement speed conditions. The shaded area represents ± 1SD from the mean. Participants' data were normalized by time and expressed as a % of the descent and ascent phase separately.

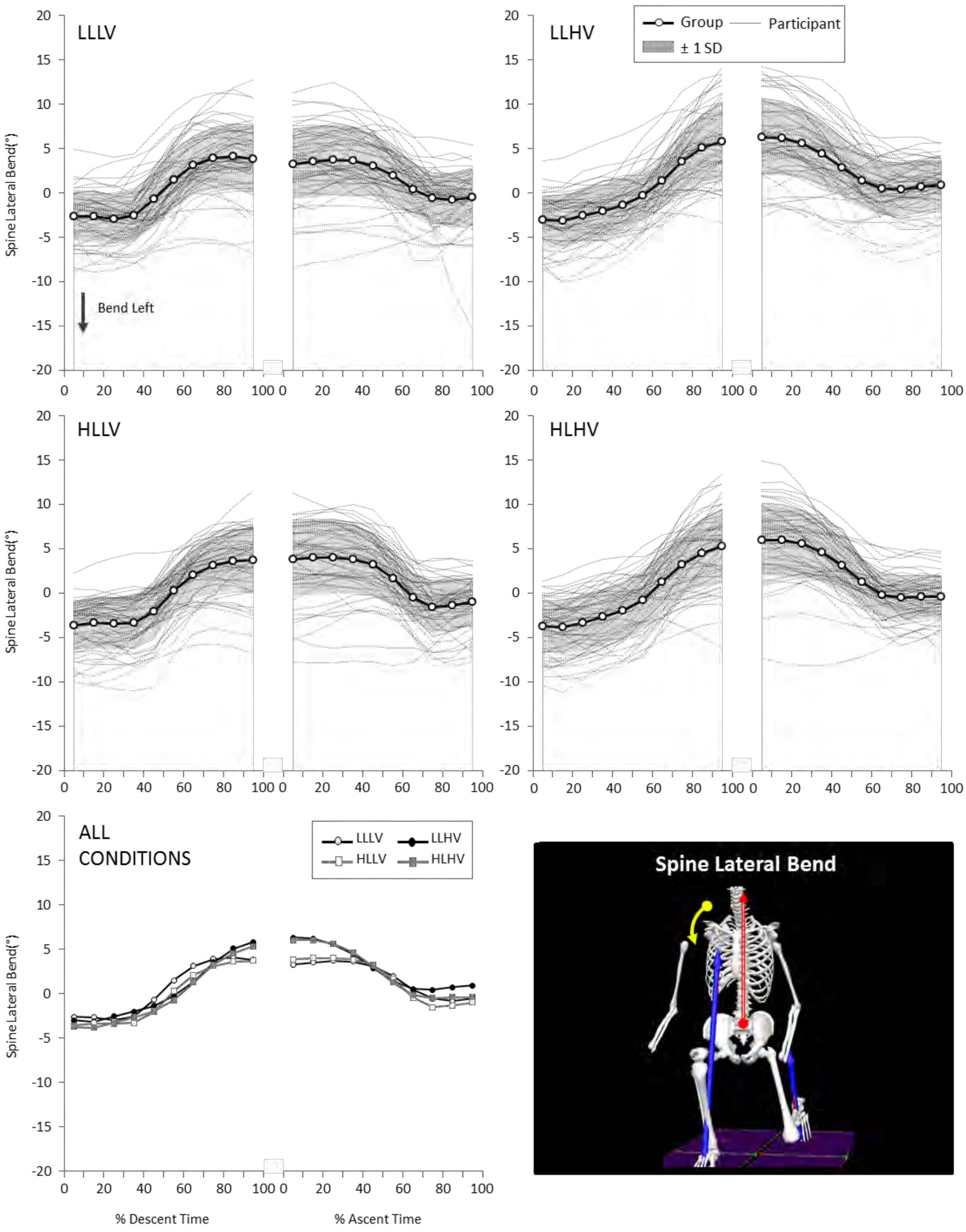


Figure B.2. The spine lateral bend exhibited by the group and all participants while LUNGING with each of the four load/movement speed conditions. The shaded area represents ± 1SD from the mean. Participants' data were normalized by time and expressed as a % of the descent and ascent phase separately.

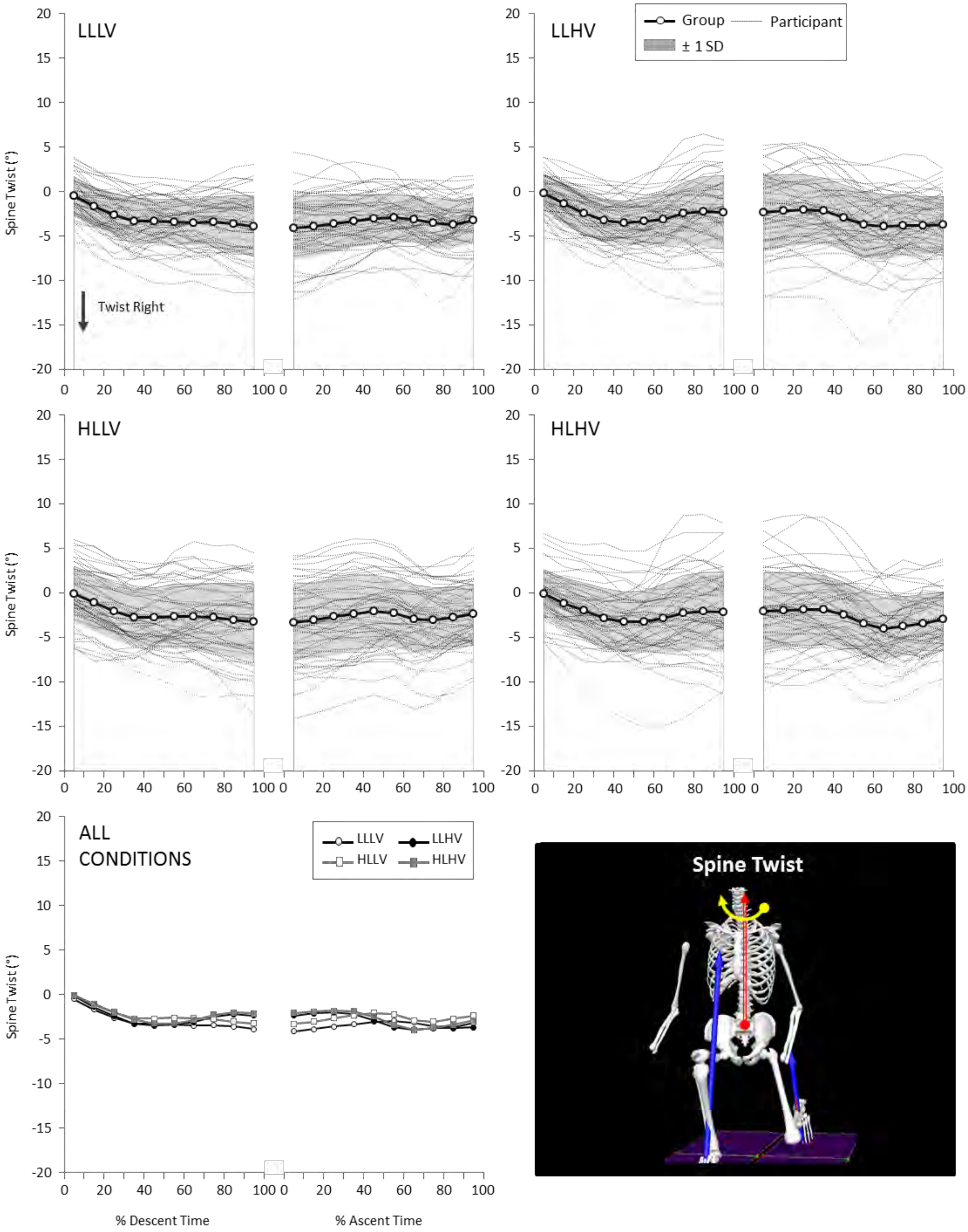


Figure B.3. The spine twist exhibited by the group and all participants while LUNGING with each of the four load/movement speed conditions. The shaded area represents ± 1SD from the mean. Participants' data were normalized by time and expressed as a % of the descent and ascent phase separately.

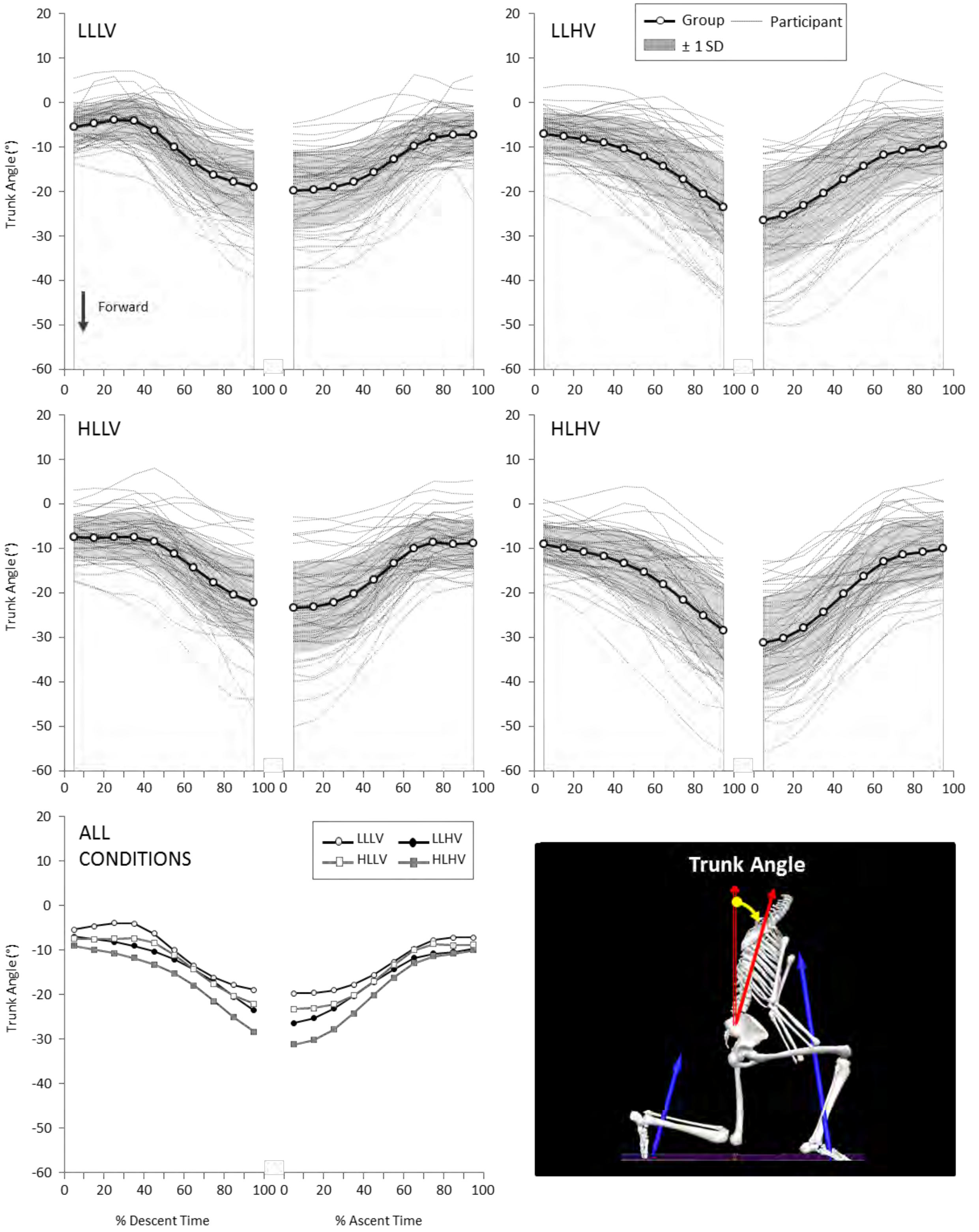


Figure B.4. The trunk angle exhibited by the group and all participants while LUNGING with each of the four load/movement speed conditions. The shaded area represents ± 1SD from the mean. Participants' data were normalized by time and expressed as a % of the descent and ascent phase separately.

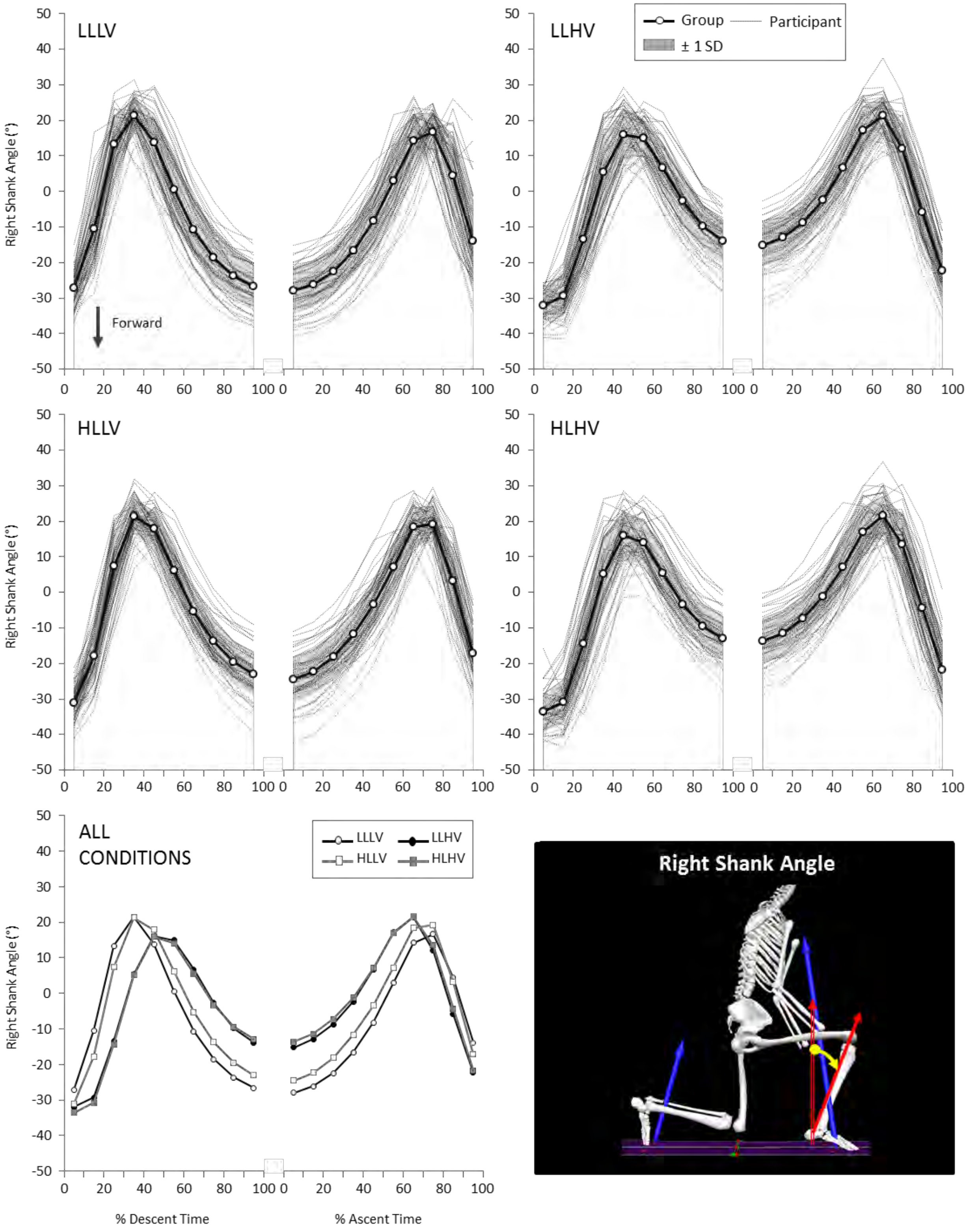


Figure B.5. The right shank angle exhibited by the group and all participants while LUNGING with each of the four load/movement speed conditions. The shaded area represents ± 1SD from the mean. Participants' data were normalized by time and expressed as a % of the descent and ascent phase separately.

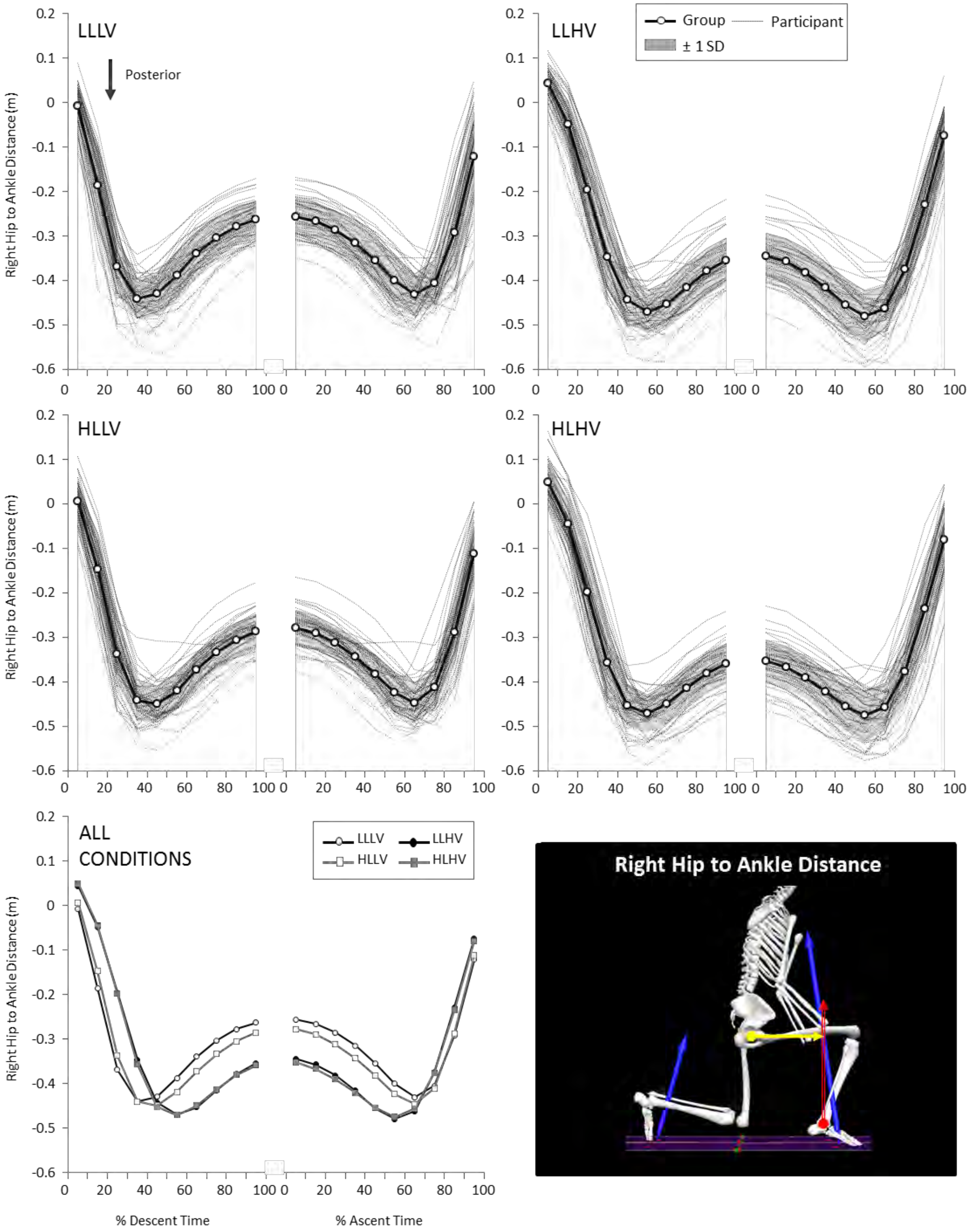


Figure B.6. The right hip to ankle distance exhibited by the group and all participants while LUNGING with each of the four load/movement speed conditions. The shaded area represents ± 1SD from the mean. Participants' data were normalized by time and expressed as a % of the descent and ascent phase separately.

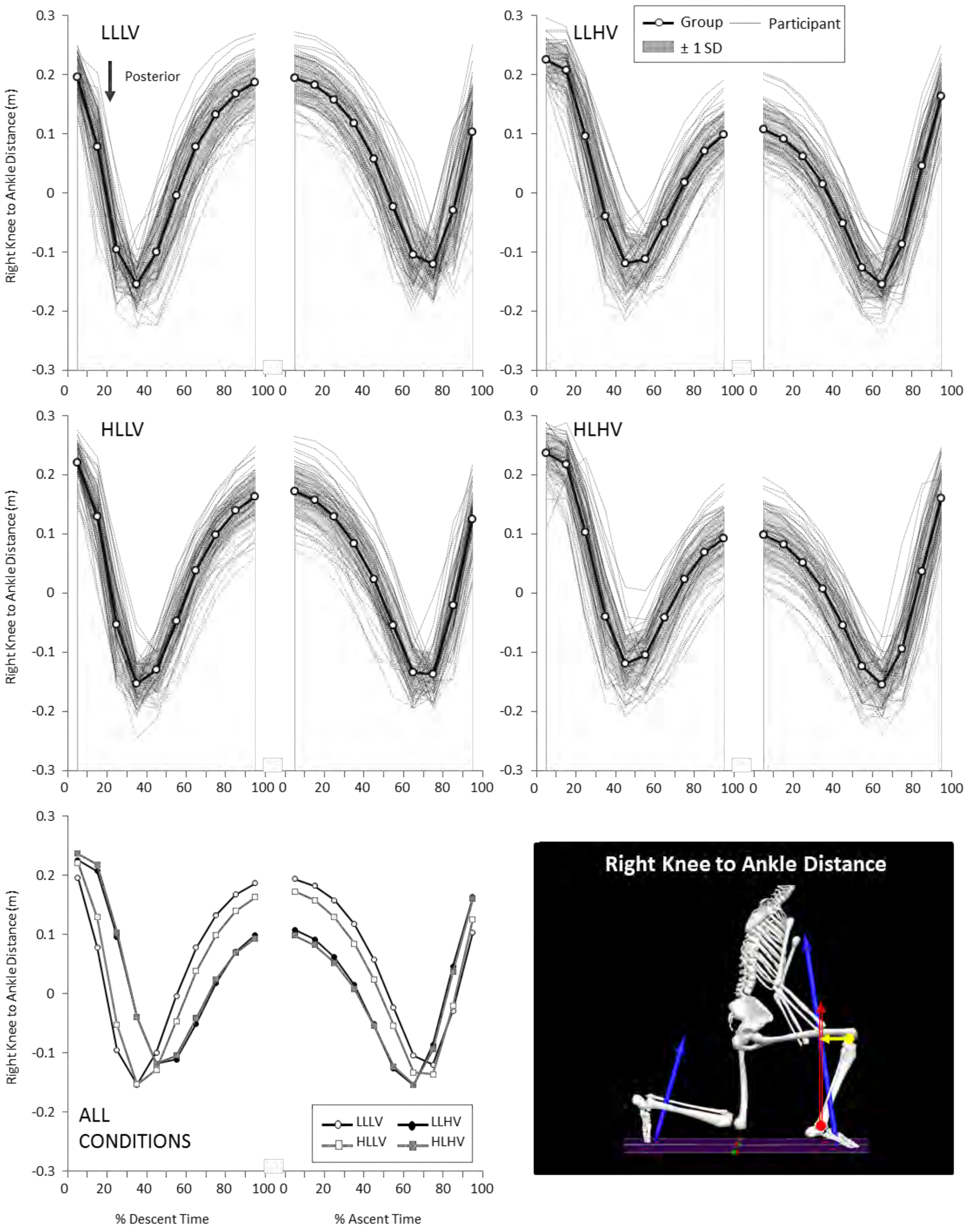


Figure B.7. The right knee to ankle distance exhibited by the group and all participants while LUNGING with each of the four load/movement speed conditions. The shaded area represents ± 1SD from the mean. Participants' data were normalized by time and expressed as a % of the descent and ascent phase separately.

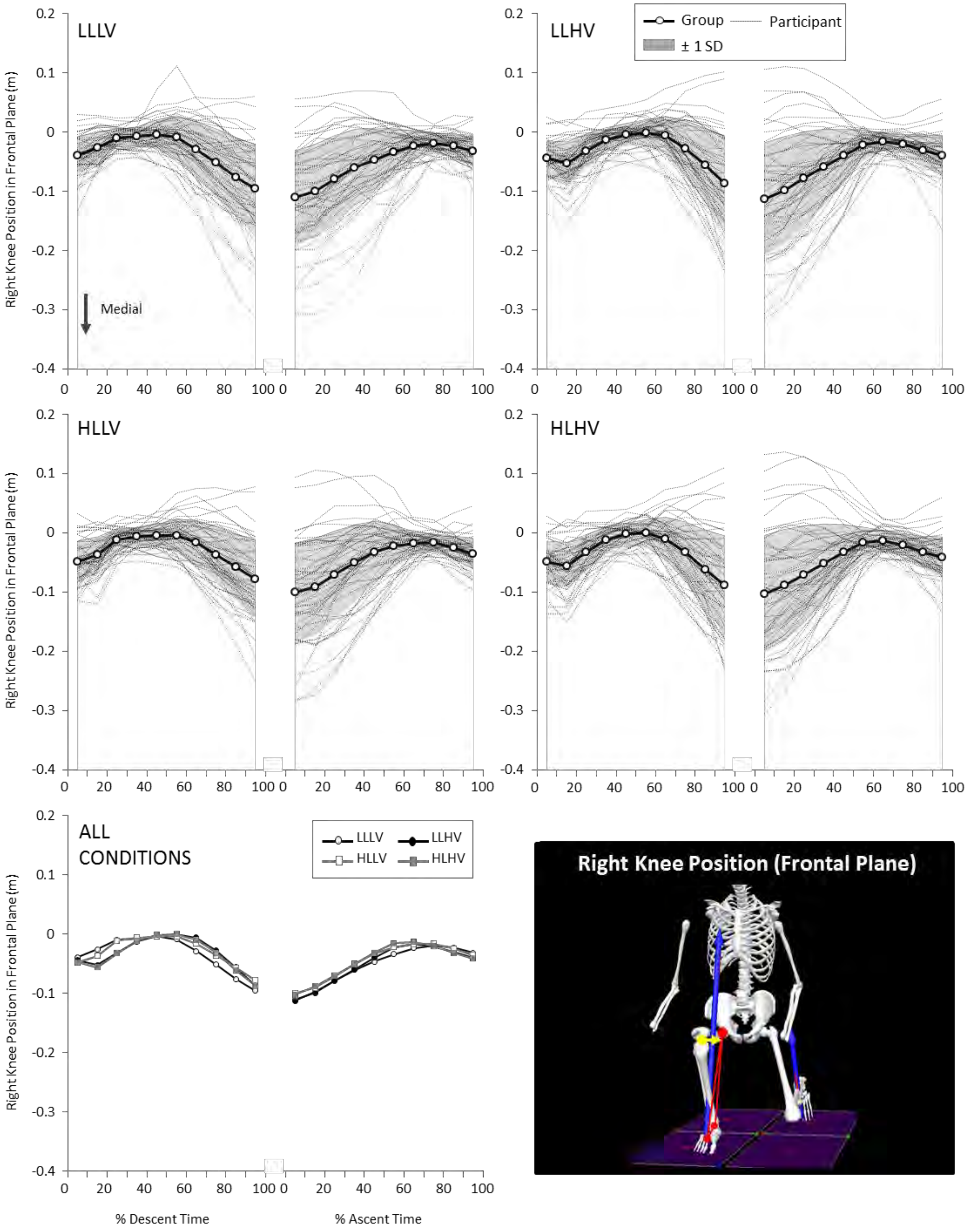


Figure B.8. The right knee position (frontal plane) exhibited by the group and all participants while LUNGING with each of the four load/movement speed conditions. The shaded area represents ± 1SD from the mean. Participants' data were normalized by time and expressed as a % of the descent and ascent phase separately.

Appendix C

SUPPLEMENT - INVESTIGATION THREE

TASK SPECIFICITY AND THE EVALUATION OF MOVEMENT PATTERNS

Figures C.1 and C.2 highlight the highest p-value found for the general task/firefighting task comparison made with each load/speed combination. Each general task and condition (e.g. low load, low velocity) is presented separately.

To highlight the differences seen amongst participants, the results in Chapter 5 presented “normalized comparisons” for each individual for the high load, high speed condition. These data describe the relationship between the range of spine and frontal plane motion observed during the general tasks to those seen while performing the simulated firefighting skills. Figure C.3 illustrates the normalized scores for each participant across the other three load/speed conditions.

The analyses described in Chapter 5 made reference to an assumption of symmetry for the lunge, push and pull tasks given that only right side data was collected. Figures C.1, C.2 and C.3 are presented to highlight the fact that if symmetry was not assumed the interpretation of any findings could have been skewed.

C.1.1. Group Behaviour

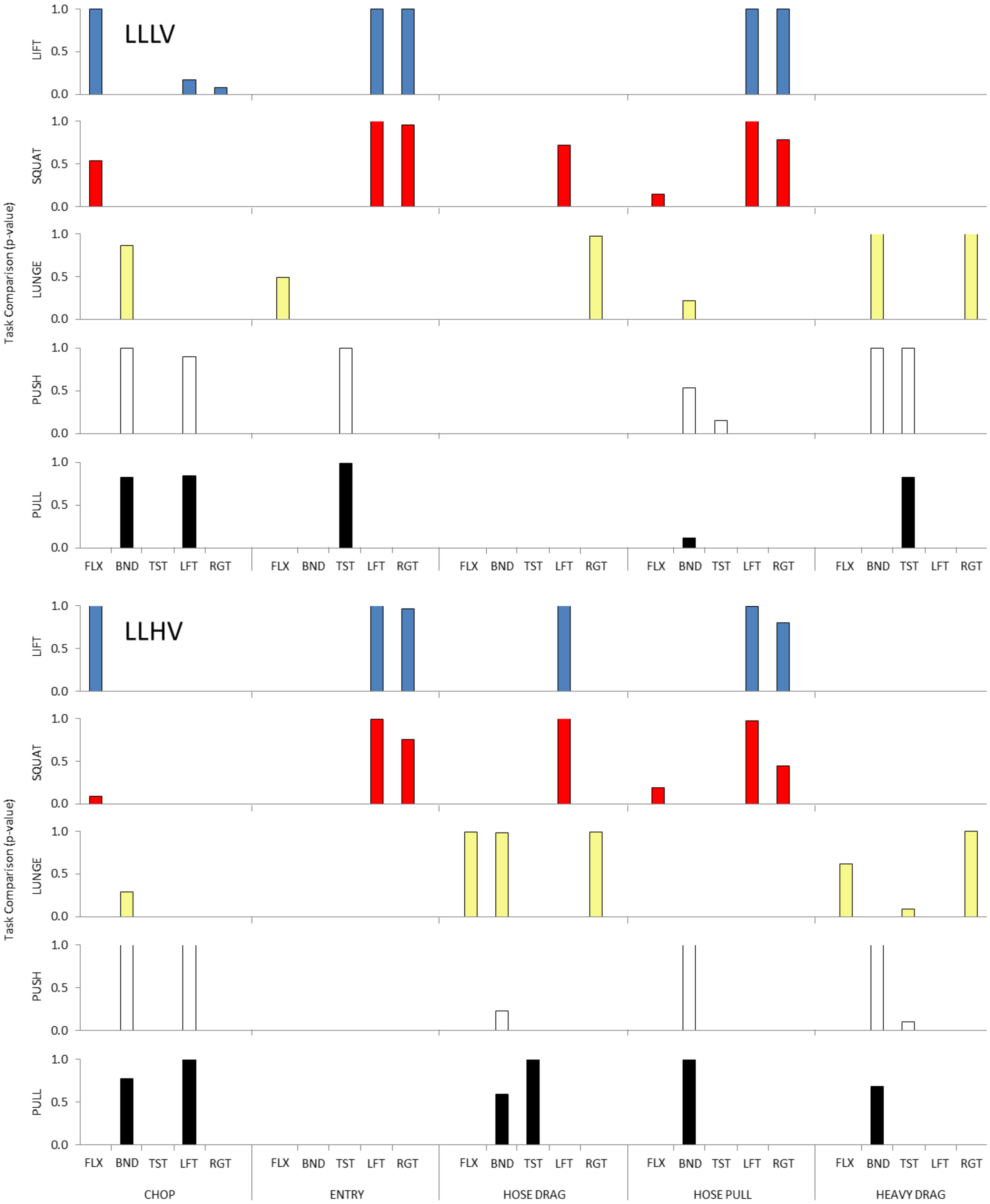


Figure C.1. A summary of the p-values describing each general task/firefighting task comparison made with the low load, low velocity (LLLV) and low load, high velocity (LLHV) conditions. No data implies that the firefighting task was significantly different ($p<0.05$) than the general pattern.

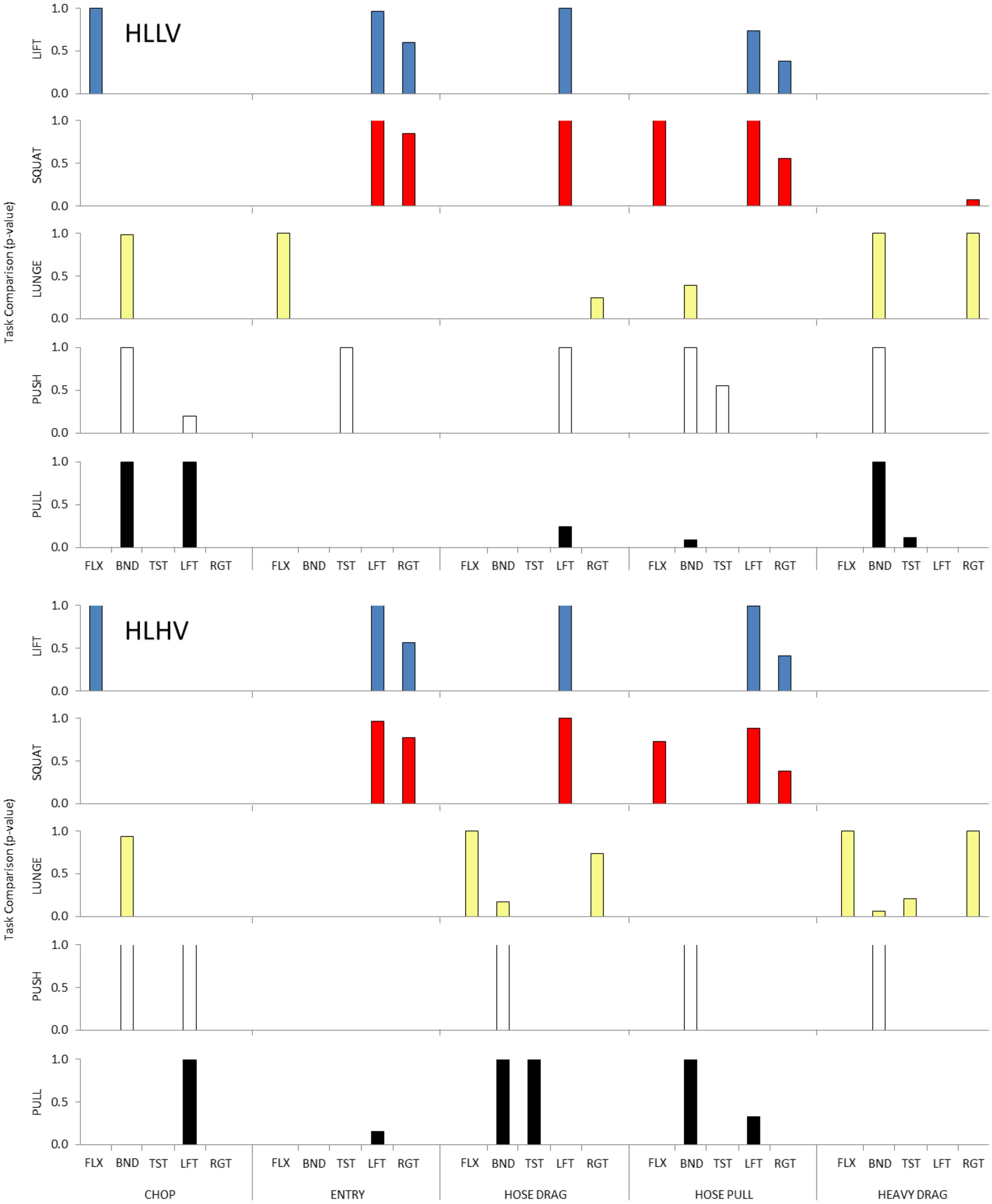


Figure C.2. A summary of the p-values describing each general task/firefighting task comparison (peak values) made with the high load, low velocity (HLLV) and high load, high velocity (HLHV) conditions. No data implies that the firefighting task was significantly different ($p<0.05$) than the general pattern.

C.1.2. Individual Differences

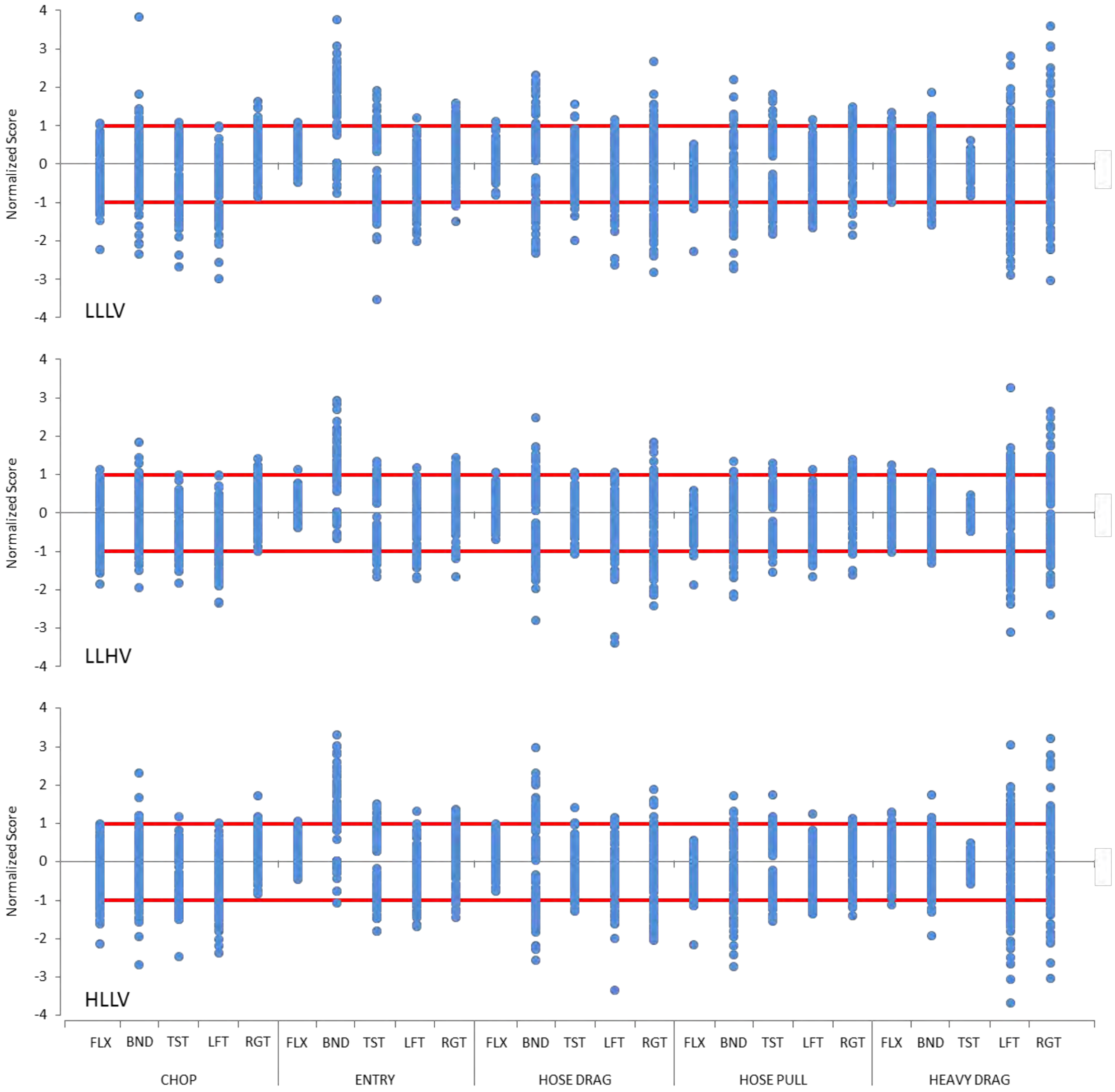


Figure C.3. Normalized maximums and minimums for each participant. Symmetry was assumed for the lunge, push and pull. The solid lines at -1 and 1 represent the subject-specific maximums and minimums observed for the general tasks. Scores outside of this range imply that the individual's general task performance was unable to capture the magnitude of deviation observed during the firefighting skill in question. Data for the low load, low velocity (LLLV), low load, high velocity (LLHV), and high load, low velocity (HLLV) condition are presented. (FLX – spine flexion/extension; BND – spine lateral bend; TST – spine twist; LFT – left knee position; and RGT – right knee position).

C.1.3. Assumption of Symmetry

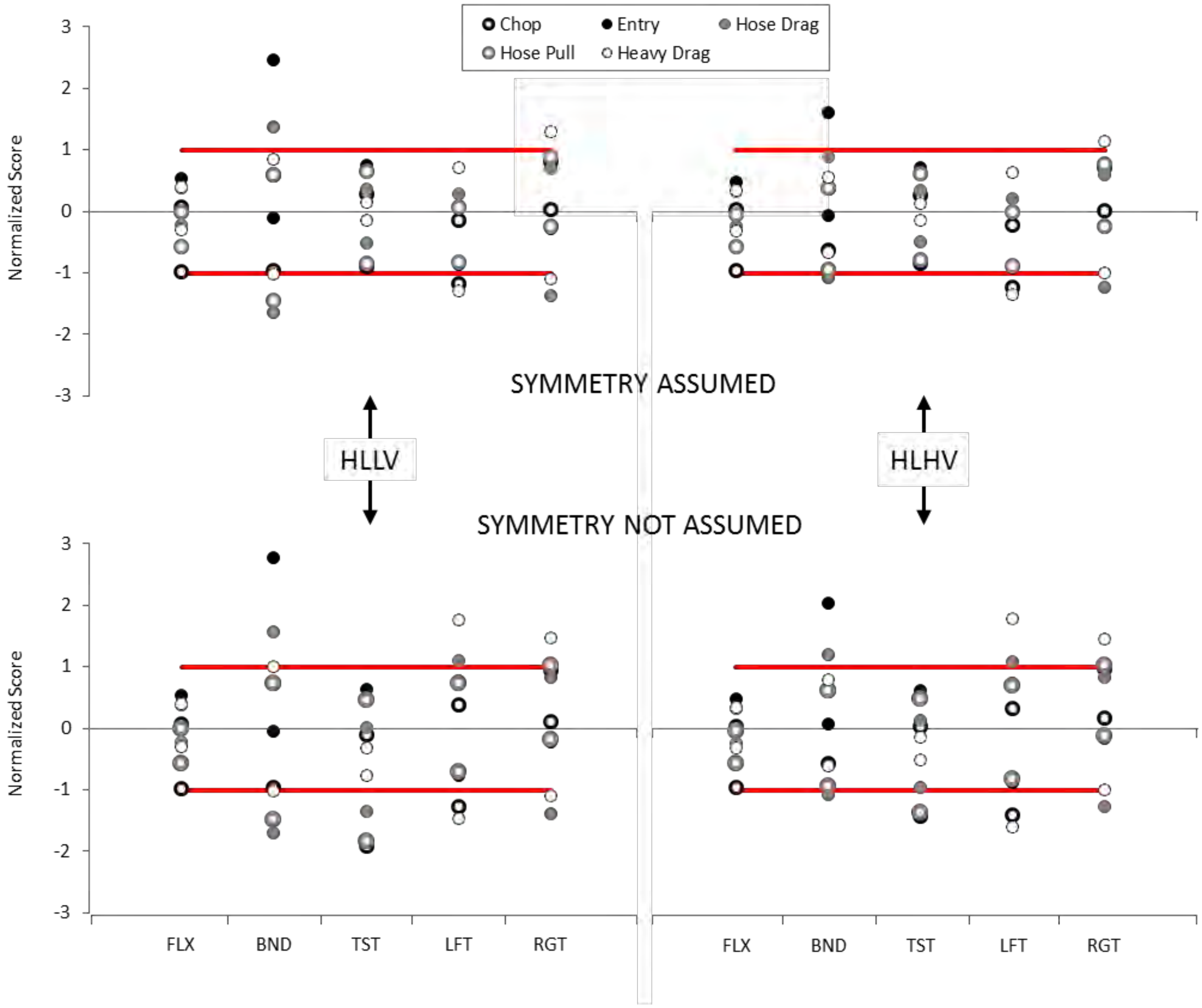


Figure C.4. Normalized maximums and minimums for each firefighting task. This figure illustrates the impact of assuming symmetry for the lunge, push and pull. The solid lines at -1 and 1 represent the maximums and minimums observed for the general tasks. Scores outside of this range imply that the group's general task performance was unable to capture the magnitude of deviation observed during the firefighting skill in question. The high load, low velocity (HLLV) and high load, high velocity conditions are presented. (FLX – spine flexion/extension; BND – spine lateral bend; TST – spine twist; LFT – left knee position; and RGT – right knee position).

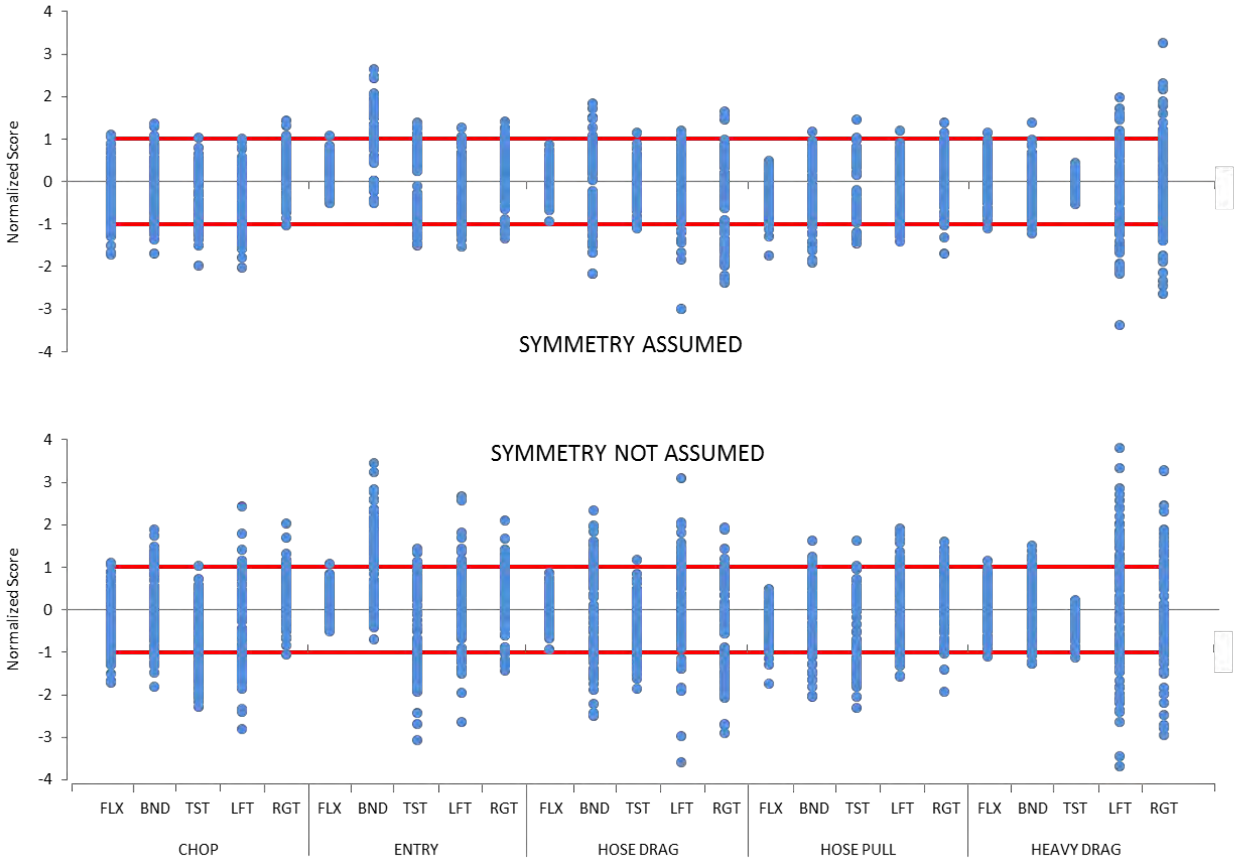


Figure C.5. Normalized maximums and minimums for each participant. This figure illustrates the impact of assuming symmetry for the lunge, push and pull. The solid lines at -1 and 1 represent the subject-specific maximums and minimums observed for the general tasks. Scores outside of this range imply that the individual's general task performance was unable to capture the magnitude of deviation observed during the firefighting skill in question. Data for the high load, high velocity condition is presented. (FLX – spine flexion/extension; BND – spine lateral bend; TST – spine twist; LFT – left knee position; and RGT – right knee position).

Table C.1. The percentage of normalized maximums and minimums across all firefighting tasks that fell beyond the limits established by the general patterns. Results were computed with and without an assumption of symmetry for the lunge, push and pull. A result of 100% would imply that in every instance possible (e.g. maximum spine flexion/extension during the hose drag) the general tasks *underestimated* the magnitude of deviation observed (i.e. high degree of specificity). Data for each of the load/movement speed conditions are presented; LLLV – low load, low velocity; LLHV – low load, high velocity; HLLV – high load, low velocity; HLHV – high load, high velocity. (FLX – spine flexion/extension; BND – spine lateral bend; TST – spine twist; LFT – left knee position; and RGT – right knee position).

	Symmetry Assumed (%)					Symmetry Not Assumed (%)				
CONDITION	FLX	BND	TST	LFT	RGT	FLX	BND	TST	LFT	RGT
LLLV	5.4	32.7	19.2	27.5	28.5	5.4	45.6	41.3	46.7	33.5
LLHV	5.6	23.5	9.2	26.9	22.3	5.6	34.8	29.4	41.7	31.9
HLLV	6.2	29.8	14.2	27.5	23.7	6.2	41.9	36.3	42.7	30.8
HLHV	5.6	18.1	8.7	21.9	18.8	5.6	30.2	27.3	34.4	28.7

Appendix D

SUPPLEMENT - INVESTIGATION FOUR

PERIODIZED EXERCISE AND THE TRANSFER OF TRAINING: CAN WE CHANGE THE WAY AN INDIVIDUAL MOVES?

The peak motions exhibited during the descent phase of the lift, squat, lunge, push and pull tasks are described in Tables D.1 – D.5, respectively. Data are presented for each intervention group and condition (e.g. low load, low velocity) separately. The magnitude of change defined as a “meaningful” within-subject difference for each variable and task is described in Table D.6. “Meaningful” differences were described as a change greater than the mean within-subject variation + 1 standard deviation.

The movement-related changes described in Chapter 6 were limited to the *peaks* of each dependent measure as the intent was to describe the maximum spine and frontal plane knee motion pre- and post-training. Further, comparing the mean spine lateral bend and twist may have little relevance given that bi-directional nature of each variable. That said, when applicable the mean adaptations post-training were quite similar to those found for the peak. For example, less spine flexion and frontal plane knee motion were exhibited by the movement-trained firefighters while lifting and squatting, respectively (Figure D.1 and D.2), while the fitness-trained individuals adopted more spine flexion when squatting post-training (Figure D.2). It should be noted however, that a range of movement patterns were used by the participants in each group. Table D.7 describes the pre, post, and change in spine flexion/extension, trunk angle and shank angle for participants who exhibited a “meaningful” spine flexion adaptation (negative or positive) while performing the low load, low velocity LIFTNG task post-training. Four individuals in the movement group did exhibit more spine flexion following the intervention, but interestingly, on average they also adopted nine more degrees of trunk lean. This finding was in contrast to a one degree change amongst fitness-trained individuals who showed a negative spine flexion adaptation. Although the findings of this investigation were limited to individual variables, there may be limitations in viewing an individual's motion in this way. Further research is needed to explore the quantification of whole-body patterns so that pre-post comparisons can be made on coordination strategies rather than single kinematic variables.

D.1.1. Group Behaviour

Table D.1. The peak (SD) motions exhibited during the descent phase of the LIFTING tasks. Data are presented for each intervention group and condition (low load, low velocity – LLLV; low load, high velocity – LLHV; high load, low velocity – HLLV; and high load, high velocity – HLHV). Positive values correspond to: FLX – flexion, TRK and SHK – forward bend, HIP – posterior displacement, KNE – anterior displacement, LFT and RGT – medial displacement.

Group	Condition	Test	FLX (°)	TRK (°)	SHK (°)	HIP (cm)	KNE (cm)	LFT (cm)	RGT (cm)
MOVEMENT	LLLV	PRE	57.5 (10.7)	74.0 (16.4)	33.2 (9.8)	18.8 (3.1)	22.8 (6.0)	2.8 (5.7)	5.0 (3.3)
		POST	54.4 (8.4)	73.1 (16.6)	30.5 (11.0)	19.4 (2.7)	21.0 (7.0)	2.0 (4.1)	4.2 (5.6)
	LLHV	PRE	58.0 (9.5)	75.3 (16.1)	30.8 (7.5)	19.6 (3.2)	21.3 (4.3)	3.1 (5.4)	6.5 (5.2)
		POST	56.5 (8.8)	75.1 (14.2)	29.3 (8.2)	20.8 (2.9)	20.2 (4.9)	2.3 (5.0)	5.4 (6.8)
	HLLV	PRE	56.7 (10.0)	72.1 (14.6)	33.7 (9.2)	19.4 (3.7)	22.8 (5.1)	4.0 (5.7)	7.7 (7.1)
		POST	53.6 (9.2)	69.9 (15.6)	31.9 (9.2)	19.8 (3.1)	21.7 (5.5)	3.4 (7.5)	5.8 (8.3)
	HLHV	PRE	57.9 (9.6)	73.8 (14.9)	31.2 (7.7)	20.5 (4.3)	21.3 (4.0)	3.0 (5.0)	6.5 (6.7)
		POST	54.8 (8.8)	70.4 (14.1)	31.1 (8.1)	20.1 (3.3)	21.3 (4.8)	3.5 (6.7)	6.1 (7.2)
FITNESS	LLLV	PRE	59.7 (9.5)	78.0 (14.6)	27.2 (9.1)	19.5 (3.2)	19.2 (6.7)	3.7 (4.9)	6.7 (5.8)
		POST	59.8 (9.8)	75.3 (14.9)	29.4 (9.1)	20.5 (2.5)	20.6 (6.2)	4.5 (5.1)	7.1 (7.1)
	LLHV	PRE	60.7 (7.7)	74.5 (11.7)	29.6 (6.6)	20.0 (2.7)	20.5 (3.8)	3.9 (4.3)	7.1 (6.4)
		POST	61.5 (9.5)	76.7 (10.7)	29.3 (9.2)	21.3 (2.6)	20.3 (5.4)	3.8 (3.6)	6.9 (6.0)
	HLLV	PRE	60.7 (9.5)	72.8 (11.2)	32.3 (6.2)	19.4 (1.8)	22.3 (4.0)	4.5 (5.9)	8.2 (7.1)
		POST	59.7 (10.4)	72.1 (12.6)	31.1 (8.3)	21.1 (1.2)	21.4 (5.0)	5.1 (5.7)	8.3 (7.4)
	HLHV	PRE	61.7 (8.5)	73.1 (10.9)	32.4 (6.5)	19.1 (2.0)	22.4 (4.4)	5.1 (5.9)	8.5 (8.5)
		POST	61.3 (11.2)	71.8 (11.7)	32.1 (6.8)	21.8 (2.9)	22.2 (3.9)	5.2 (4.8)	8.1 (6.6)
CONTROL	LLLV	PRE	58.0 (11.6)	67.7 (15.9)	36.1 (9.7)	17.9 (3.5)	24.1 (5.6)	2.5 (4.0)	6.8 (6.4)
		POST	59.1 (11.9)	74.9 (22.4)	31.7 (13.1)	19.4 (3.2)	21.3 (8.2)	4.2 (6.1)	7.8 (7.7)
	LLHV	PRE	56.6 (11.3)	67.6 (18.1)	35.2 (11.1)	18.9 (5.6)	23.2 (6.4)	4.4 (8.2)	8.0 (5.9)
		POST	57.1 (13.9)	75.4 (25.0)	29.8 (14.4)	20.2 (4.4)	19.9 (8.8)	4.2 (6.1)	7.2 (7.1)
	HLLV	PRE	55.3 (11.0)	65.4 (17.7)	36.1 (10.9)	18.0 (3.6)	23.6 (6.4)	3.4 (4.7)	8.6 (6.7)
		POST	54.9 (13.3)	69.5 (23.6)	33.7 (13.3)	20.6 (3.8)	22.1 (8.0)	3.6 (5.7)	8.5 (8.2)
	HLHV	PRE	55.3 (10.5)	65.2 (16.5)	35.9 (9.6)	18.6 (4.3)	23.5 (5.8)	2.7 (4.0)	8.8 (7.1)
		POST	55.9 (11.9)	69.1 (20.8)	34.5 (10.4)	20.8 (4.3)	22.6 (5.9)	4.8 (7.5)	10.1 (9.5)

FLX – spine flexion/extension; TRK – trunk angle; SHK – shank angle; HIP – hip to ankle distance; KNE – Knee to ankle distance; LFT – left knee position; and RGT – right knee position

Table D.2. The peak (SD) motions exhibited during the descent phase of the SQUATTING tasks. Data are presented for each intervention group and condition (low load, low velocity – LLLV; low load, high velocity – LLHV; high load, low velocity – HLLV; and high load, high velocity – HLHV). Positive values correspond to: FLX – flexion, TRK and SHK – forward bend, HIP – posterior displacement, KNE – anterior displacement, LFT and RGT – medial displacement.

Group	Condition	Test	FLX (°)	TRK (°)	SHK (°)	HIP (cm)	KNE (cm)	LFT (cm)	RGT (cm)
MOVEMENT	LLLV	PRE	52.0 (14.3)	54.6 (11.4)	37.7 (7.1)	18.5 (3.4)	25.7 (4.2)	3.0 (4.9)	7.0 (6.5)
		POST	54.7 (8.9)	55.7 (7.5)	35.2 (5.9)	19.8 (3.2)	24.4 (3.7)	2.0 (4.1)	5.4 (5.2)
	LLHV	PRE	54.6 (15.1)	56.7 (10.1)	34.7 (5.4)	19.6 (2.5)	24.0 (3.5)	4.4 (7.0)	8.5 (8.1)
		POST	54.7 (10.4)	55.1 (8.1)	33.5 (5.9)	20.3 (2.5)	23.4 (3.9)	2.8 (5.4)	6.3 (5.7)
	HLLV	PRE	49.3 (13.5)	54.2 (9.3)	38.3 (7.3)	17.2 (2.9)	26.0 (4.7)	3.9 (5.7)	9.0 (7.1)
		POST	49.6 (8.6)	54.5 (7.0)	36.9 (6.7)	18.0 (2.9)	25.3 (4.2)	3.0 (5.2)	6.0 (5.2)
	HLHV	PRE	52.6 (14.2)	56.7 (8.1)	34.9 (5.5)	18.7 (2.8)	24.0 (3.6)	3.8 (6.2)	9.3 (7.6)
		POST	51.3 (11.1)	55.1 (7.8)	34.6 (6.1)	19.0 (2.7)	23.9 (4.0)	3.0 (5.7)	6.0 (5.8)
FITNESS	LLLV	PRE	51.6 (14.1)	52.8 (12.6)	40.2 (6.9)	16.4 (4.2)	26.9 (3.7)	3.8 (3.7)	9.0 (7.3)
		POST	57.1 (13.2)	58.3 (9.4)	35.9 (5.9)	20.4 (3.3)	24.5 (3.6)	5.4 (5.2)	11.4 (9.2)
	LLHV	PRE	49.3 (11.1)	51.3 (12.1)	38.4 (6.5)	17.2 (3.5)	25.8 (3.3)	4.3 (5.5)	9.6 (7.2)
		POST	56.5 (10.0)	57.1 (8.2)	35.2 (5.1)	20.3 (3.1)	24.1 (2.9)	5.3 (5.6)	9.9 (7.3)
	HLLV	PRE	46.4 (11.7)	20.0 (11.0)	41.4 (6.8)	14.9 (3.9)	27.5 (4.1)	3.7 (4.7)	9.4 (8.7)
		POST	52.8 (12.6)	56.1 (9.7)	39.1 (6.9)	17.9 (3.8)	26.2 (3.2)	4.3 (4.1)	10.6 (8.6)
	HLHV	PRE	47.8 (90.3)	52.3 (10.0)	37.9 (6.2)	16.4 (3.8)	25.6 (3.5)	5.1 (5.1)	8.3 (8.3)
		POST	53.5 (10.7)	57.2 (9.2)	35.9 (6.2)	19.1 (3.7)	24.4 (3.0)	4.6 (4.4)	9.3 (7.6)
CONTROL	LLLV	PRE	51.2 (16.5)	48.8 (14.0)	41.4 (7.5)	14.9 (4.2)	27.8 (4.3)	4.3 (4.9)	8.5 (7.3)
		POST	49.4 (16.3)	50.4 (11.0)	40.8 (7.6)	17.0 (3.5)	27.2 (4.5)	3.0 (4.0)	8.1 (7.9)
	LLHV	PRE	47.2 (13.3)	49.1 (10.8)	38.0 (5.8)	16.3 (3.6)	26.0 (4.1)	3.7 (5.8)	6.9 (5.6)
		POST	48.7 (13.9)	51.5 (8.8)	37.3 (6.3)	18.5 (3.1)	25.4 (4.1)	3.4 (5.4)	7.1 (6.0)
	HLLV	PRE	44.3 (14.7)	47.3 (13.2)	41.1 (7.6)	14.3 (4.1)	27.5 (4.3)	3.0 (3.7)	6.6 (5.6)
		POST	44.4 (12.6)	49.1 (10.3)	40.8 (7.1)	15.8 (3.2)	27.2 (4.1)	3.3 (6.5)	6.9 (6.4)
	HLHV	PRE	45.3 (11.7)	48.4 (8.7)	38.2 (5.5)	15.5 (2.8)	26.1 (3.8)	4.4 (7.6)	7.2 (6.4)
		POST	47.0 (13.3)	51.4 (9.4)	38.4 (6.4)	16.9 (2.6)	25.9 (4.0)	3.9 (8.0)	7.7 (6.0)

FLX – spine flexion/extension; TRK – trunk angle; SHK – shank angle; HIP – hip to ankle distance; KNE – Knee to ankle distance; LFT – left knee position; and RGT – right knee position

Table D.3. The peak (SD) motions exhibited during the descent phase of the LUNGING tasks. Data are presented for each intervention group and condition (low load, low velocity – LLLV; low load, high velocity – LLHV; high load, low velocity – HLLV; and high load, high velocity – HLHV). Positive values correspond to: FLX – flexion, BND and TST – maximum range; TRK and SHK – forward bend, HIP – posterior displacement, KNE – anterior displacement, RGT – medial displacement.

Group	Condition	Test	FLX (°)	BND (°)	TST (°)	TRK (°)	SHK (°)	HIP (cm)	KNE (cm)	RGT (cm)
MOVEMENT	LLLV	PRE	22.4 (11.9)	8.8 (2.6)	6.3 (2.5)	22.9 (7.7)	31.4 (3.3)	47.1 (5.0)	22.2 (2.4)	12.3 (7.7)
		POST	22.5 (8.9)	7.4 (1.7)	5.8 (1.8)	22.0 (6.8)	33.2 (6.2)	48.9 (6.7)	23.2 (4.1)	12.4 (7.3)
	LLHV	PRE	34.7 (13.0)	9.9 (3.8)	6.6 (2.0)	29.2 (10.0)	33.9 (4.1)	49.3 (5.3)	23.8 (2.8)	13.8 (8.6)
		POST	32.6 (8.9)	8.1 (3.3)	6.0 (2.5)	27.5 (8.5)	35.5 (5.1)	49.3 (4.6)	24.8 (3.5)	13.7 (6.7)
	HLLV	PRE	26.3 (11.9)	8.6 (3.4)	5.9 (2.2)	24.8 (9.3)	33.7 (3.5)	16.9 (4.5)	23.7 (2.1)	12.5 (7.0)
		POST	26.2 (8.7)	6.7 (2.1)	5.2 (1.6)	24.9 (8.0)	34.8 (6.6)	47.3 (4.6)	24.2 (4.2)	12.0 (8.2)
	HLHV	PRE	37.3 (12.3)	9.6 (3.8)	6.9 (2.7)	33.8 (10.3)	36.6 (3.0)	49.3 (4.7)	25.5 (2.2)	13.3 (8.4)
		POST	35.1 (8.9)	7.8 (2.5)	5.8 (2.1)	30.8 (8.3)	36.4 (6.9)	48.4 (4.0)	25.2 (4.4)	14.3 (8.3)
FITNESS	LLLV	PRE	22.8 (9.4)	10.5 (3.4)	6.5 (2.2)	21.5 (9.2)	33.0 (4.3)	45.3 (2.9)	23.0 (2.2)	13.4 (7.6)
		POST	23.2 (10.7)	8.9 (2.8)	5.7 (1.8)	21.5 (9.6)	33.3 (3.9)	46.4 (3.2)	23.0 (2.1)	15.8 (7.9)
	LLHV	PRE	31.0 (12.2)	12.0 (4.2)	7.8 (2.1)	27.9 (10.0)	35.1 (3.8)	48.7 (5.3)	24.4 (2.3)	13.7 (7.7)
		POST	34.1 (12.0)	11.2 (3.7)	7.2 (1.7)	27.5 (8.5)	36.2 (4.7)	49.2 (3.6)	24.9 (2.8)	17.6 (8.8)
	HLLV	PRE	24.4 (9.7)	10.3 (3.5)	6.0 (1.8)	24.4 (11.8)	34.7 (4.0)	45.8 (2.8)	23.1 (3.4)	12.1 (7.4)
		POST	25.6 (10.3)	9.4 (2.5)	5.2 (1.4)	24.6 (9.4)	35.8 (4.2)	46.8 (3.8)	23.7 (2.9)	15.2 (8.1)
	HLHV	PRE	35.1 (10.0)	12.9 (4.1)	7.0 (2.5)	32.6 (11.6)	36.5 (4.7)	48.1 (3.7)	25.2 (3.0)	13.6 (7.9)
		POST	36.0 (10.9)	12.1 (3.3)	6.1 (1.9)	33.4 (9.2)	36.8 (5.0)	48.8 (3.6)	25.2 (3.1)	15.9 (8.1)
CONTROL	LLLV	PRE	21.8 (11.0)	8.5 (3.0)	7.5 (2.3)	17.3 (7.9)	32.6 (4.4)	46.6 (5.2)	22.8 (2.9)	12.9 (6.0)
		POST	23.0 (10.7)	10.3 (3.6)	8.4 (2.8)	18.1 (8.8)	34.9 (4.9)	47.7 (4.8)	24.2 (3.2)	11.5 (5.5)
	LLHV	PRE	28.5 (10.4)	10.9 (4.9)	7.0 (1.5)	21.5 (9.4)	35.6 (5.2)	48.2 (4.4)	24.7 (3.3)	12.9 (6.1)
		POST	32.7 (9.9)	13.9 (4.8)	7.7 (2.3)	26.5 (8.9)	36.3 (5.5)	48.9 (3.7)	25.1 (3.1)	13.9 (6.8)
	HLLV	PRE	24.8 (10.0)	8.7 (3.8)	6.1 (2.1)	20.9 (8.4)	33.1 (5.2)	48.0 (3.3)	23.1 (3.4)	10.7 (5.0)
		POST	28.2 (8.5)	11.0 (3.5)	6.7 (2.5)	24.5 (9.1)	34.0 (4.3)	48.0 (3.4)	23.7 (2.9)	11.9 (6.1)
	HLHV	PRE	32.8 (8.3)	10.9 (3.6)	6.5 (1.3)	26.7 (9.1)	35.3 (5.6)	47.7 (4.6)	24.5 (3.6)	11.6 (5.5)
		POST	35.2 (11.0)	14.1 (3.4)	7.8 (2.4)	30.9 (9.3)	37.0 (5.7)	50.0 (4.2)	25.6 (3.5)	12.4 (6.3)

FLX – spine flexion/extension; BND – spine lateral bend; TST – spine twist; TRK – trunk angle; SHK – shank angle; HIP – hip to ankle distance; KNE – Knee to ankle distance; and RGT – right knee position

Table D.4. The peak (SD) motions exhibited during the descent phase of the PUSHING tasks. Data are presented for each intervention group and condition (low load, low velocity – LLLV; low load, high velocity – LLHV; high load, low velocity – HLLV; and high load, high velocity – HLHV). Positive values correspond to: FLX – flexion, BND and TST – maximum range; TRK and SHK – forward bend, HIP – posterior displacement, KNE – anterior displacement, LFT – medial displacement.

Group	Condition	Test	FLX (°)	BND (°)	TST (°)	TRK (°)	SHK (°)	HIP (cm)	KNE (cm)	LFT (cm)
MOVEMENT	LLLV	PRE	5.2 (5.9)	7.9 (5.1)	20.0 (5.3)	19.5 (7.9)	0.8 (8.6)	30.6 (5.0)	0.5 (6.3)	-0.2 (3.0)
		POST	5.6 (5.9)	4.5 (3.7)	15.1 (5.0)	19.3 (10.7)	2.7 (7.7)	29.3 (4.9)	2.0 (5.6)	0.2 (2.3)
	LLHV	PRE	7.5 (6.3)	11.7 (7.5)	31.6 (7.0)	19.1 (8.3)	6.5 (7.6)	31.3 (5.8)	4.8 (5.5)	0.7 (3.9)
		POST	8.5 (7.3)	8.4 (6.3)	24.6 (7.0)	20.2 (10.4)	5.6 (6.3)	31.5 (3.7)	4.1 (5.6)	0.9 (3.0)
	HLLV	PRE	5.5 (5.9)	9.8 (5.6)	23.7 (6.9)	20.1 (8.4)	4.3 (7.3)	30.7 (6.1)	3.1 (5.4)	-0.8 (3.6)
		POST	6.3 (6.2)	6.6 (5.6)	18.5 (6.4)	20.9 (8.4)	7.0 (6.0)	28.9 (4.1)	5.2 (4.3)	-0.3 (3.1)
	HLHV	PRE	8.6 (7.2)	14.2 (7.9)	30.9 (7.0)	20.8 (8.7)	9.2 (7.1)	32.0 (5.9)	6.6 (5.1)	0.9 (4.5)
		POST	9.1 (8.0)	9.3 (6.4)	24.3 (7.4)	23.0 (10.3)	11.1 (5.4)	29.0 (4.2)	8.2 (3.9)	0.9 (3.8)
FITNESS	LLLV	PRE	8.1 (7.8)	8.1 (3.3)	24.1 (7.7)	22.6 (10.4)	3.3 (10.0)	29.8 (3.2)	2.5 (7.0)	0.8 (2.9)
		POST	6.6 (7.9)	5.5 (3.2)	20.5 (4.8)	19.9 (9.6)	0.6 (6.1)	30.3 (4.5)	0.7 (4.4)	0.8 (2.0)
	LLHV	PRE	8.1 (6.9)	11.5 (5.5)	32.3 (6.6)	22.3 (9.7)	7.5 (5.6)	30.5 (4.8)	5.6 (4.3)	1.5 (2.7)
		POST	10.2 (10.4)	10.3 (7.7)	28.7 (6.1)	23.6 (10.5)	7.1 (7.4)	32.0 (4.8)	5.5 (5.6)	2.2 (3.1)
	HLLV	PRE	7.5 (6.3)	9.8 (3.9)	27.0 (7.3)	24.8 (7.7)	6.2 (8.4)	29.8 (5.1)	4.7 (6.3)	-0.2 (2.2)
		POST	9.9 (9.6)	7.7 (4.1)	22.8 (5.7)	25.6 (9.5)	8.5 (8.1)	30.0 (5.0)	6.5 (6.1)	0.5 (3.3)
	HLHV	PRE	9.8 (6.6)	13.6 (6.9)	33.2 (5.1)	25.6 (9.2)	12.3 (5.0)	29.4 (4.2)	8.9 (3.7)	1.5 (2.8)
		POST	12.7 (10.4)	11.8 (8.7)	29.4 (6.4)	27.4 (10.2)	11.2 (6.6)	31.4 (5.8)	8.3 (4.6)	1.7 (2.9)
CONTROL	LLLV	PRE	5.0 (6.6)	5.4 (2.3)	23.2 (8.0)	15.7 (8.0)	0.0 (9.2)	29.6 (4.1)	-0.3 (7.0)	-0.1 (2.8)
		POST	3.9 (4.8)	6.1 (2.7)	23.6 (7.8)	16.6 (6.3)	-3.6 (6.2)	32.7 (3.2)	-2.6 (4.6)	-0.2 (2.7)
	LLHV	PRE	5.5 (6.1)	9.0 (3.7)	32.4 (8.3)	16.8 (8.6)	4.8 (7.8)	30.3 (3.1)	3.6 (5.9)	0.6 (3.6)
		POST	5.5 (7.7)	8.5 (4.3)	31.3 (5.5)	17.6 (8.2)	1.6 (5.5)	33.1 (3.0)	1.2 (4.2)	0.6 (3.3)
	HLLV	PRE	3.8 (6.5)	9.3 (4.2)	27.2 (5.7)	18.4 (8.3)	4.8 (8.1)	29.7 (4.3)	3.4 (6.0)	-0.8 (3.9)
		POST	3.7 (6.4)	8.9 (3.9)	26.2 (7.7)	19.0 (7.2)	2.2 (6.9)	32.4 (4.4)	1.5 (5.0)	-0.8 (3.4)
	HLHV	PRE	6.8 (7.4)	12.3 (5.2)	33.6 (7.6)	18.7 (9.3)	7.4 (8.5)	31.0 (4.7)	5.3 (6.3)	0.6 (4.4)
		POST	7.1 (7.3)	11.9 (4.0)	33.2 (8.7)	20.8 (6.3)	6.5 (6.4)	32.2 (3.6)	4.8 (4.6)	0.1 (4.7)

FLX – spine flexion/extension; BND – spine lateral bend; TST – spine twist; TRK – trunk angle; SHK – shank angle; HIP – hip to ankle distance; KNE – Knee to ankle distance; and LFT – left knee position.

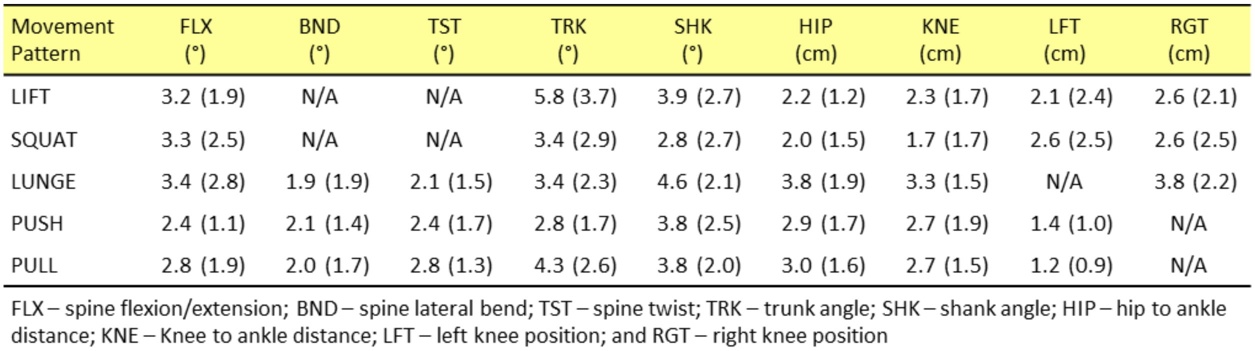
Table D.5. The peak (SD) motions exhibited during the descent phase of the PULLING tasks. Data are presented for each intervention group and condition (low load, low velocity – LLLV; low load, high velocity – LLHV; high load, low velocity – HLLV; and high load, high velocity – HLHV). Positive values correspond to: FLX – flexion, BND and TST – maximum range; TRK and SHK – forward bend, HIP – posterior displacement, KNE – anterior displacement, LFT – medial displacement.

Group	Condition	Test	FLX (°)	BND (°)	TST (°)	TRK (°)	SHK (°)	HIP (cm)	KNE (cm)	LFT (cm)
MOVEMENT	LLLV	PRE	12.9 (8.0)	4.1 (2.3)	24.1 (7.4)	16.4 (10.5)	-6.4 (7.2)	32.0 (5.4)	-4.8 (5.3)	-0.2 (2.6)
		POST	13.5 (8.6)	3.9 (1.8)	19.7 (6.5)	19.3 (12.3)	-7.7 (5.5)	33.2 (4.0)	-5.7 (4.1)	-0.1 (2.2)
	LLHV	PRE	18.7 (7.8)	6.6 (2.9)	34.2 (7.3)	23.0 (10.4)	-0.4 (7.4)	35.5 (5.6)	-0.3 (5.5)	2.1 (3.8)
		POST	16.1 (9.9)	5.9 (3.0)	28.0 (7.9)	21.0 (12.9)	-3.9 (9.1)	36.2 (4.7)	-2.8 (6.4)	0.2 (2.9)
	HLLV	PRE	17.5 (8.2)	4.8 (2.2)	29.6 (8.9)	20.1 (9.7)	-8.4 (4.7)	36.4 (5.3)	-6.2 (3.4)	-0.1 (3.2)
		POST	16.9 (10.2)	4.8 (2.7)	24.0 (8.7)	21.4 (12.2)	-8.8 (5.6)	38.1 (4.6)	-6.4 (4.2)	-0.6 (2.5)
	HLHV	PRE	21.4 (8.0)	7.0 (2.6)	37.0 (8.7)	24.4 (10.2)	-1.5 (7.0)	40.0 (4.5)	-1.2 (5.1)	2.2 (3.5)
		POST	20.1 (10.4)	6.2 (3.1)	30.8 (8.8)	23.7 (12.2)	-6.0 (7.5)	41.0 (5.0)	-4.3 (5.3)	0.9 (2.9)
FITNESS	LLLV	PRE	16.3 (8.8)	4.8 (2.2)	26.8 (6.4)	19.6 (10.2)	-7.6 (4.2)	33.0 (6.0)	-5.5 (2.9)	-0.1 (2.0)
		POST	13.9 (9.0)	3.9 (2.0)	23.6 (5.5)	18.6 (11.4)	-7.8 (5.6)	34.9 (4.7)	-5.4 (3.8)	0.9 (2.6)
	LLHV	PRE	17.7 (6.4)	5.6 (2.6)	37.9 (7.3)	24.0 (8.2)	-1.4 (6.9)	37.0 (6.6)	-0.9 (5.1)	1.2 (2.3)
		POST	20.3 (10.1)	5.5 (4.1)	32.5 (9.5)	26.2 (11.1)	-0.6 (9.3)	39.2 (5.2)	0.0 (6.5)	2.7 (2.8)
	HLLV	PRE	19.7 (8.7)	7.1 (2.8)	32.1 (8.1)	24.4 (9.0)	-7.3 (5.6)	38.5 (7.2)	-5.2 (4.3)	1.4 (3.1)
		POST	20.2 (9.8)	5.2 (1.7)	29.4 (8.9)	24.5 (10.0)	-6.6 (5.9)	40.3 (6.1)	-4.4 (4.0)	1.4 (2.2)
	HLHV	PRE	23.3 (7.8)	6.8 (2.7)	39.9 (9.1)	28.2 (8.8)	-2.2 (8.1)	41.1 (5.9)	-1.4 (5.9)	2.7 (2.6)
		POST	23.8 (9.9)	5.0 (1.7)	34.0 (9.1)	28.3 (11.4)	0.6 (8.9)	41.5 (4.5)	0.9 (6.5)	3.1 (3.2)
CONTROL	LLLV	PRE	14.1 (10.9)	5.1 (3.0)	27.1 (8.9)	17.6 (10.0)	-9.9 (4.5)	33.3 (7.2)	-7.3 (3.5)	1.4 (2.1)
		POST	9.4 (6. 4)	4.3 (2.4)	27.8 (9.7)	14.1 (8.4)	-11.2 (4.6)	34.3 (3.6)	-7.9 (3.5)	0.3 (2.2)
	LLHV	PRE	16.6 (8.9)	6.4 (3.2)	37.7 (7.1)	20.1 (9.0)	-5.2 (5.5)	35.9 (7.0)	-3.7 (3.9)	1.3 (2.4)
		POST	14.8 (9.3)	7.2 (4.0)	38.3 (7.8)	18.4 (11.8)	-6.7 (7.0)	37.2 (4.4)	-4.5 (5.0)	1.8 (2.4)
	HLLV	PRE	15.5 (10.2)	6.2 (2.9)	32.9 (7.5)	19.3 (10.2)	-10.2 (5.4)	37.2 (6.3)	-7.3 (3.9)	0.1 (2.5)
		POST	15.0 (9.4)	5.9 (3.8)	32.0 (7.3)	18.8 (11.5)	-9.7 (6.5)	37.9 (4.2)	-6.8 (4.7)	1.2 (2.8)
	HLHV	PRE	18.6 (10.1)	6.4 (3.8)	39.7 (8.8)	19.7 (11.5)	-4.8 (7.5)	38.8 (5.5)	-3.2 (5.4)	2.1 (2.5)
		POST	19.2 (7.8)	8.4 (4.1)	38.1 (8.0)	20.2 (10.5)	-5.9 (6.2)	40.2 (4.3)	-3.8 (4.5)	2.4 (3.6)

FLX – spine flexion/extension; BND – spine lateral bend; TST – spine twist; TRK – trunk angle; SHK – shank angle; HIP – hip to ankle distance; KNE – Knee to ankle distance; and LFT – left knee position.

D.1.2. “Meaningful” Within-Subject Changes

Table D.6. The mean (SD) within-subject variation used to describe “meaningful” changes for each variable and task. The data depict the largest variation computed across all load/movement speed conditions for any metric (i.e. maximum, minimum or mean) and phase (e.g. decent or ascent) during the pre-test. “Meaningful” differences were described as a change greater than the within-subject variation + 1SD. N/A signifies that the variable was not computed.



Movement Pattern	FLX (°)	BND (°)	TST (°)	TRK (°)	SHK (°)	HIP (cm)	KNE (cm)	LFT (cm)	RGT (cm)
LIFT	3.2 (1.9)	N/A	N/A	5.8 (3.7)	3.9 (2.7)	2.2 (1.2)	2.3 (1.7)	2.1 (2.4)	2.6 (2.1)
SQUAT	3.3 (2.5)	N/A	N/A	3.4 (2.9)	2.8 (2.7)	2.0 (1.5)	1.7 (1.7)	2.6 (2.5)	2.6 (2.5)
LUNGE	3.4 (2.8)	1.9 (1.9)	2.1 (1.5)	3.4 (2.3)	4.6 (2.1)	3.8 (1.9)	3.3 (1.5)	N/A	3.8 (2.2)
PUSH	2.4 (1.1)	2.1 (1.4)	2.4 (1.7)	2.8 (1.7)	3.8 (2.5)	2.9 (1.7)	2.7 (1.9)	1.4 (1.0)	N/A
PULL	2.8 (1.9)	2.0 (1.7)	2.8 (1.3)	4.3 (2.6)	3.8 (2.0)	3.0 (1.6)	2.7 (1.5)	1.2 (0.9)	N/A

FLX – spine flexion/extension; BND – spine lateral bend; TST – spine twist; TRK – trunk angle; SHK – shank angle; HIP – hip to ankle distance; KNE – Knee to ankle distance; LFT – left knee position; and RGT – right knee position

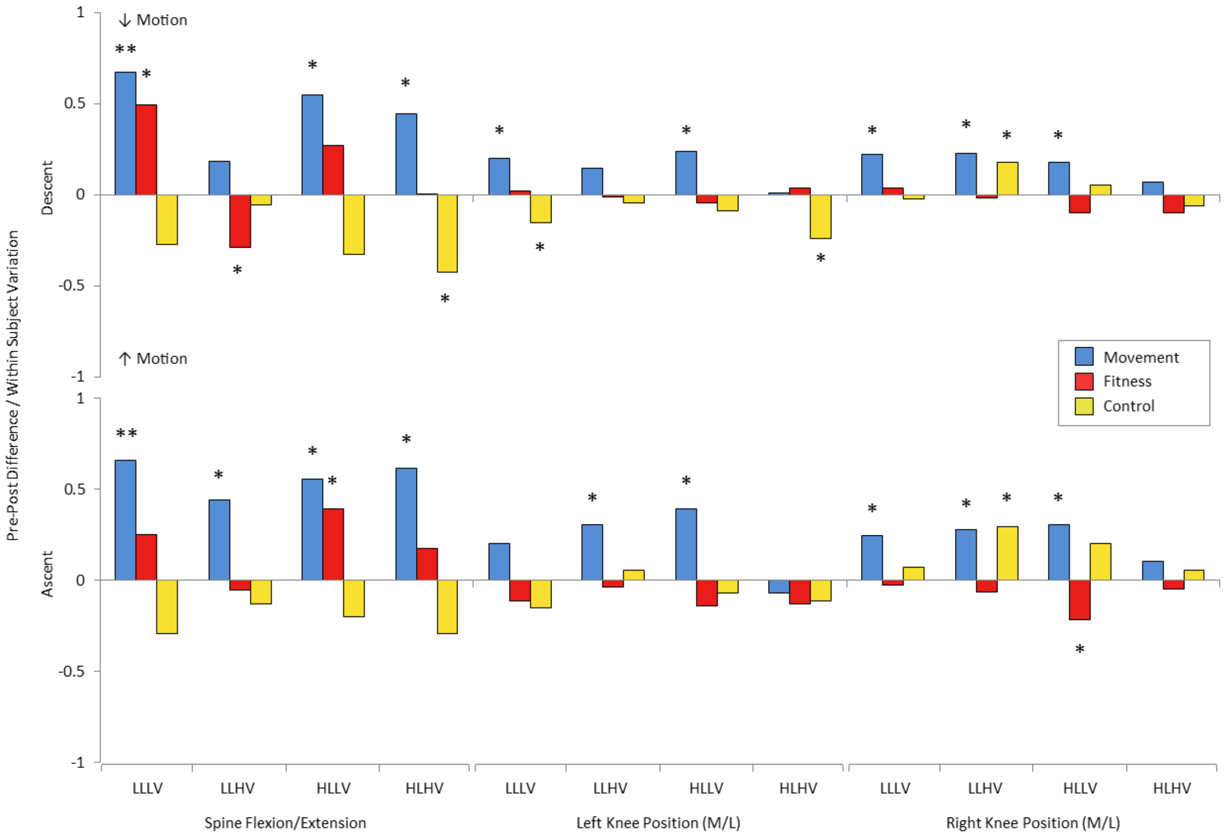


Figure D.1. Lifting-related training adaptations in the mean spine and knee motion for each condition (load x speed) and group. Changes are presented as a function of the maximum within-subject variation + 1SD observed for a given variable (i.e. that of the maximum, minimum or mean of either phase for any load or speed) for the descent (top) and ascent (bottom) phase of each lift. The effect size (ES) of each difference is also described by the inclusion of one (ES=0.2-0.4), two (0.4-0.6) or three (>0.6) asterisks. A positive change reflects less motion post-training.

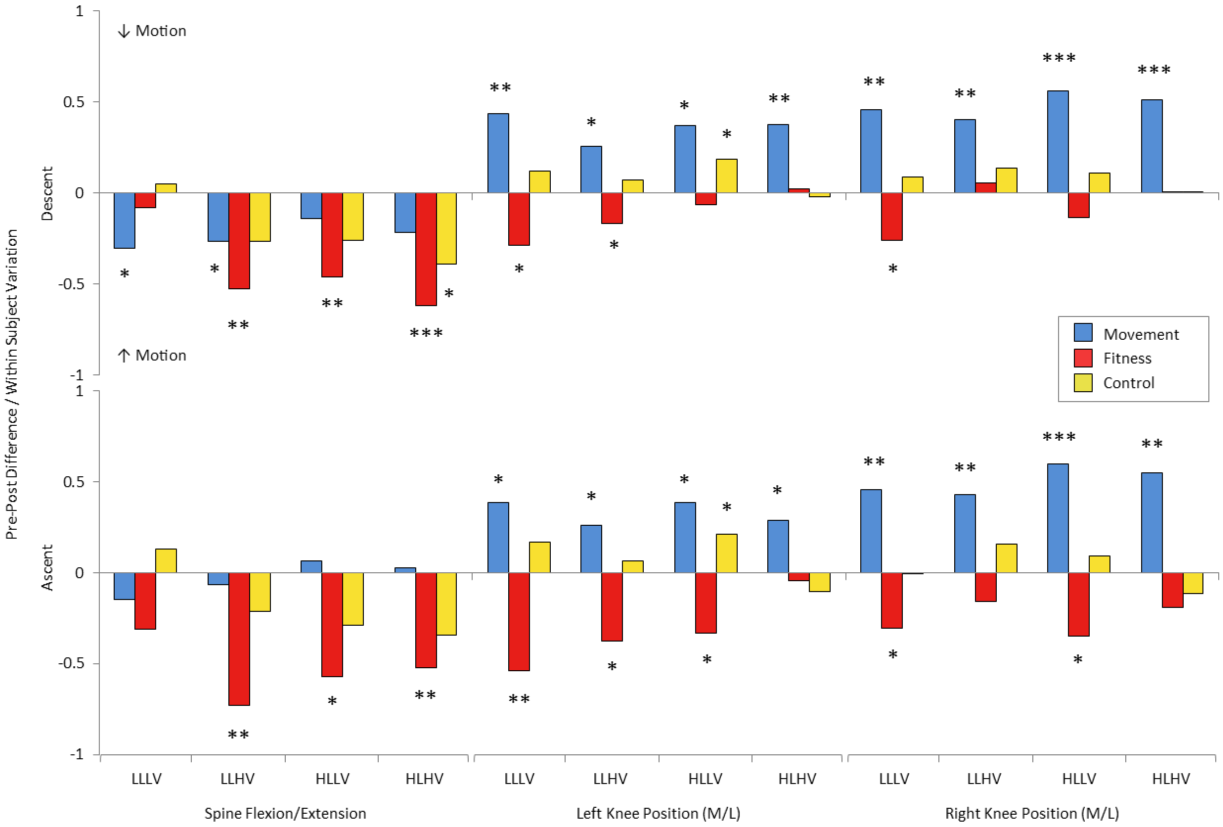


Figure D.2. Squatting-related training adaptations in the mean spine and knee motion for each condition (load x speed) and group. Changes are presented as a function of the maximum within-subject variation + 1SD observed for a given variable (i.e. that of the maximum, minimum or mean of either phase for any load or speed) for the descent (top) and ascent (bottom) phase of each lift. The effect size (ES) of each difference is also described by the inclusion of one (ES=0.2-0.4), two (0.4-0.6) or three (>0.6) asterisks. A positive change reflects less motion post-training.

D.1.3. Individual Differences

Table D.7. A range of movement patterns were used by the participants in each group. This table describes the pre, post, and change in spine flexion/extension, trunk angle and shank angle for participants who exhibited a "meaningful" spine flexion adaptation (negative or positive) while performing the low load, low velocity LIFITNG task post-training. Note the between-group differences in the trunk angle amongst participants who demonstrated an increase in spine motion.

TRAINING EFFECT	INTERVENTION GROUP		Spine Flexion (°)			Trunk Angle (°)			Shank Angle (°)		
		Subject	Pre	Post	Δ	Pre	Post	Δ	Pre	Post	Δ
↓ Spine Motion	MOVEMENT-ORIENTED	S02	47.2	39.9	-7.2	54.7	50.2	-4.6	45.8	43.0	-2.8
		S07	64.7	49.8	-14.9	73.6	56.1	-17.5	34.9	38.7	3.9
		S10	54.6	39.3	-15.4	63.1	61.4	-1.8	33.7	30.8	-2.9
		S62	63.0	53.9	-9.1	76.9	58.2	-18.6	30.0	39.0	8.9
		S74	59.5	49.3	-10.1	71.0	72.8	1.8	33.8	32.0	-1.8
		S77	79.1	65.4	-13.6	69.4	81.3	11.9	39.5	25.2	-14.3
		S79	75.4	65.8	-9.6	86.8	79.2	-7.6	32.2	32.0	-0.2
		MEAN	63.4	51.9	-11.4	70.8	65.6	-5.2	35.7	34.4	-1.3
		SD	11.2	10.8	3.2	10.2	20.9	10.7	5.3	12.4	7.1
	FITNESS-ORIENTED	S25	70.4	56.6	-13.8	63.4	55.6	-7.8	39.1	45.8	6.7
		S47	47.2	41.3	-6.0	62.9	50.2	-12.7	34.6	38.3	3.7
		S56	55.8	49.7	-6.1	65.6	71.7	6.2	32.1	31.3	-0.8
		MEAN	57.8	49.2	-8.6	64.0	59.2	-4.8	35.2	38.5	3.2
		SD	11.7	7.7	4.5	1.4	11.2	9.8	3.5	7.3	3.8
	CONTROL	S27	62.6	47.4	-15.2	48.0	47.1	-0.9	44.8	43.1	-1.7
		S82	65.5	60.2	-5.3	80.6	79.1	-1.5	34.4	35.4	1.0
		S83	62.0	39.8	-22.2	62.0	53.7	-8.4	35.8	38.3	2.5
		MEAN	63.4	49.1	-14.2	63.6	60.0	-3.6	38.3	38.9	0.6
		SD	1.9	10.3	8.5	16.3	20.5	4.1	5.6	7.7	2.1
↑ Spine Motion	MOVEMENT-ORIENTED	S12	44.9	56.3	11.4	45.5	56.7	11.2	46.4	40.8	-5.6
		S39	44.6	57.0	12.5	59.0	72.3	13.3	43.3	37.2	-6.2
		S55	42.1	48.2	6.1	61.3	70.1	8.8	31.1	29.0	-2.1
		S75	66.0	71.8	5.8	67.5	70.1	2.6	33.3	29.2	-4.0
		MEAN	49.4	58.3	8.9	58.3	67.3	9.0	38.5	34.1	-4.5
		SD	11.1	9.8	3.5	9.3	13.9	4.7	7.5	9.3	1.8
	FITNESS-ORIENTED	S04	49.1	57.0	7.9	70.7	74.0	3.3	28.3	27.4	-0.9
		S15	66.4	73.6	7.3	77.3	71.7	-5.5	29.7	37.4	7.7
		S57	65.9	71.1	5.2	76.3	81.4	5.1	34.1	31.2	-2.9
		MEAN	60.5	67.3	6.8	74.8	75.7	0.9	30.7	32.0	1.3
		SD	9.8	8.9	1.4	3.5	9.2	5.7	3.0	8.6	5.6
	CONTROL	S03	76.7	82.9	6.2	108.2	113.4	5.2	13.1	14.3	1.2
		S09	50.6	55.8	5.2	76.3	72.8	-3.5	21.1	19.3	-1.8
		S11	34.0	39.7	5.7	33.8	35.4	1.6	52.1	54.5	2.4
		S68	43.2	52.7	9.5	71.6	84.6	13.1	41.4	36.5	-4.9
		S80	57.5	65.7	8.2	75.5	95.9	20.5	25.3	20.3	-4.9
		S16	55.9	68.4	12.5	62.5	66.6	4.1	35.8	34.6	-1.2
		S63	54.5	59.6	5.1	71.1	70.5	-0.5	30.5	32.0	1.5
		MEAN	53.2	60.7	7.5	71.3	77.1	5.8	31.3	30.2	-1.1
		SD	13.3	13.6	2.7	21.9	30.2	8.3	13.1	16.1	3.0

Appendix E

TECHNICAL NOTE ONE

MIGHT THE INTERPRETATION OF BETWEEN-DAY CHANGES IN JOINT ANGLES, FORCES AND MOMENTS BE INFLUENCED BY VARIATION IN THE LINK SEGMENT MODEL?

E.1. INTRODUCTION

Between-day variation in the position of a body segment's endpoints and thus the orientiation of its local coodinate system could skew the interpretation of between-day changes in any kinematic or kinetic dependent measure. This study examined the influence of link segment model (LSM) variation on the calculation of a joint angle, force and moment.

E.2. RESEARCH DESIGN AND METHODS

Infrared markers (Optotrak® Certus™, NDI, Waterloo, ON, Canada) were secured to one participant's pelvis and right thigh, shank and foot. Each segment's endpoints were located with a digitizing probe and used to define a segment-fixed (local) axis system. Motion trials were collected to compute a "functional" hip joint center (HJC) and "functional" knee joint axis (KJA) (Schwartz and Rozumalski, 2005). This protocol was repeated 20 times so that 20 unique LSMs could be created. On two separate occasions (reference sessions) the participant performed 3 countermovement vertical jumps. A force platform (AMTI, Watertown, MA, U.S.A.) was used to measure ground reaction forces and moments.

The positions of each segment’s endpoints were described relative to a local origin (anatomical landmark located with the highest degree of reliability across all 20 LSMs) so that the proximal and distal radius and segment length could be maintained when applied to the reference sessions. As a result, each unique LSM could be used with the same motion data, thus providing an opportunity to examine the influence of variation in the model design process. This entire protocol was repeated twice using different segment endpoint definitions: A) digitized anatomical landmarks, and B) “functional” joints. In each instance knee joint angles, reaction forces and net joint moments were computed for the 20 LSMs. Between-LSM variation was described by the maximum deviation (2 SD) observed across all 20 LSMs at any point during the motion trial.

E.3. RESULTS

Slight variation in the position of each segment’s endpoints (0.9 – 9.0 mm) altered the orientation of the thigh and shank coordinate systems, thus introducing LSM-dependent variability into the computation of all knee joint angles, forces and moments (Table E.1). However, the magnitude of this variation was highly dependent on the segment endpoint definition (Figure E.1); using a “functionally”-defined HJC and KJA minimized the variation in each dependent measure (Table E.1). Knee joint angles and net joint moments were more sensitive to variation in the LSM than the reaction forces (Table E.1).

Table E.1. Maximum variation across all 20 LSMs created using: A) digitized landmarks, and B) functional joints. The data are presented as a mean (SD) of the same 6 jump trials and expressed as an absolute difference and percentage of the total range observed (max-min).

		Right Knee Angle (°)			Right Knee Force (N)			Right Knee Moment (Nm)		
Model	Variation	Flex/Ext	Ab/Add	Int/Ext	Med/Lat	Ant/Post	Vert	Flex/Ext	Ab/Add	Int/Ext
A	2 SD	2.4 (0.1)	8.0 (0.0)	6.7 (0.4)	43 (7)	14 (6)	4 (0)	11.7 (5.6)	13.3 (3.0)	1.3 (0.4)
	% Range	2.1 (0.1)	33.2 (2.2)	27.4 (3.7)	20 (4)	2 (1)	0 (0)	5.7 (1.5)	14.3 (2.7)	6.5 (1.4)
B	2 SD	0.0 (0.0)	0.0 (0.0)	0.1 (0.0)	3 (1)	3 (0)	3 (0)	7.7 (2.3)	3.3 (1.3)	1.0 (0.2)
	% Range	0.0 (0.0)	0.2 (0.0)	0.4 (0.0)	2 (1)	1 (0)	0 (0)	3.9 (0.4)	3.8 (0.7)	5.3 (1.1)

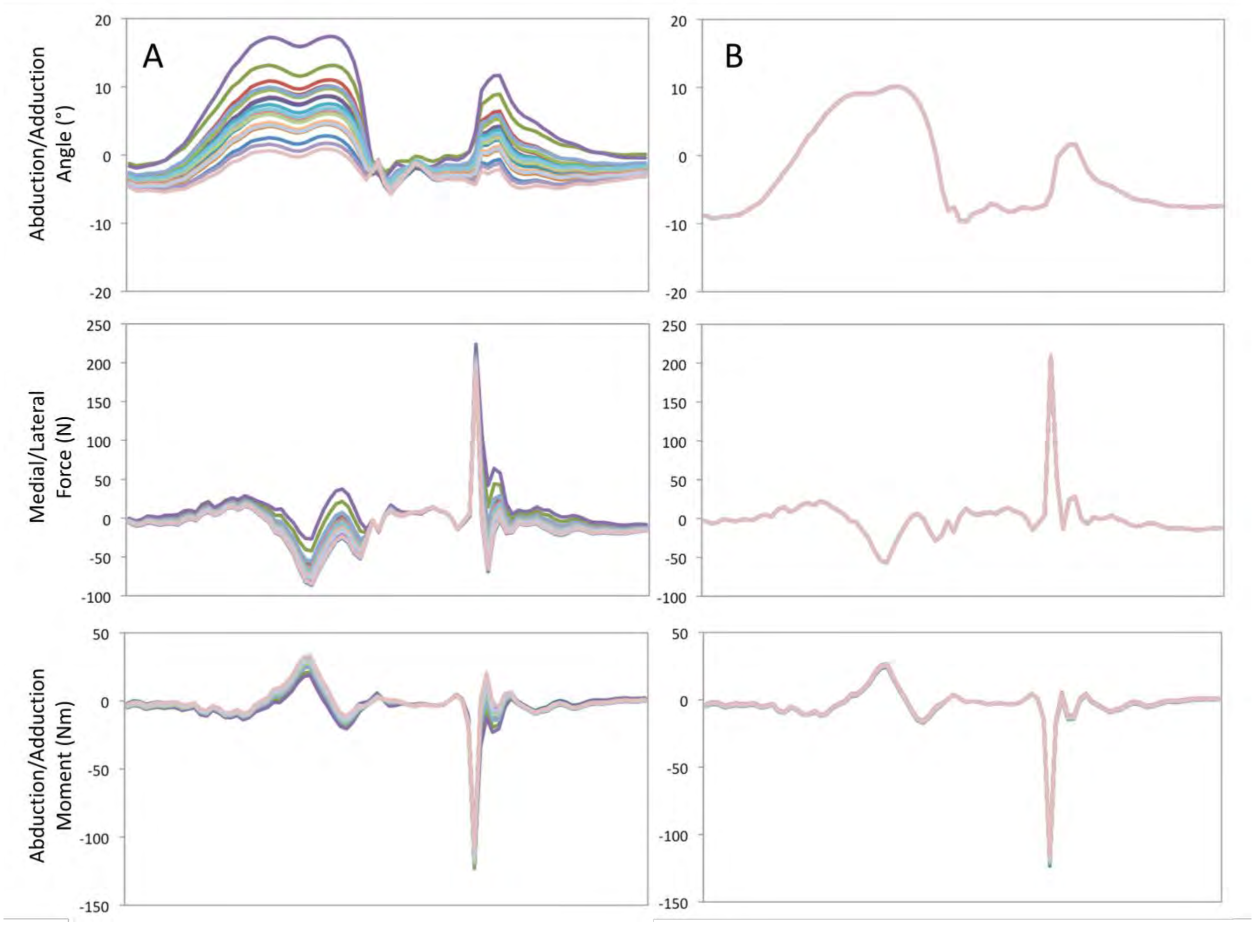


Figure E.1. Knee angles (abd/add), forces (med/lat) and moments (abd/add) computed with 20 distinct LSMs using: A) anatomical landmarks, and B) "functional" joints.

E.3. CONCLUSION

The interpretation of between-day changes (or between-study comparisons) can be influenced by the methods used to create the LSM, particularly if computing discrete measures such as a peak joint angle or net joint moment (e.g. 13.3 Nm deviation in the knee abduction moment). Using functionally defined segment endpoints may help to minimize the degree of variation introduced via the digitization or palpation of anatomical landmarks, and thus provide a more stable way to create the LSM for between-day comparisons.

Appendix F

TECHNICAL NOTE TWO

DOES THE ELIMINATION OF THIGH MARKERS INFLUENCE THE BETWEEN-DAY VARIATION IN JOINT ANGLES?

E.1. INTRODUCTION

Tracking the thigh with its adjacent segments (i.e pelvis and shank) may minimize the influence of motion artifact and thus provide a better estimation of any measure referenced in the thigh coordinate system. This study examined the influence of thigh tracking on the between-day variation and magnitude of knee joint motion.

E.2. RESEARCH DESIGN AND METHODS

Infrared markers (Optotrak® Certus™, NDI, Waterloo, ON, Canada), were secured to one participant's pelvis and right thigh, shank and foot. Each segment's endpoints were located with a digitizing probe and used to define a segment-fixed (local) axis system. Motion trials were collected to compute a "functional" hip joint center (HJC) and "functional" knee joint axis (KJA) (Schwartz and Rozumalski, 2005). This protocol was repeated 20 times so that 20 unique LSMs could be created. On two separate occasions (reference sessions) the participant performed 3 vertical jumps.

The positions of each segment's endpoints were described relative to a local origin (landmark located with the highest degree of reliability) so that the proximal and distal radius and segment length could be maintained when applied to the reference sessions. As a result, each unique LSM could be used with the same motion data, thus providing an opportunity to contrast two thigh tracking methods: A) using one and two digitized landmarks (DL) defined in the pelvis and shank (PS) coordinate systems, respectively, and B) using a rigid marker cluster fixed to the thigh (TH). In each instance segments endpoints were defined using anatomical landmarks. A third instance (method C) was included for comparative purposes whereby the LSM was created using "functional" joints (FJ) and tracked with the rigid marker cluster (as in B). Knee joint angles were calculated for each of the 20 LSMs. Between-LSM variation (2 SD) and maximums and minimums were extracted for comparison.

E.3. RESULTS

Tracking the thigh segment using landmarks defined in the pelvis and shank coordinate systems did not reduce the between-LSM variation, in comparison to the rigid cluster method (Table F.1). In fact, substantial variation was noted in the abduction/adduction and internal/external rotation angles for both tracking methods when anatomical landmarks were used to define the segment endpoints (Figure F.1). However, adopting the pelvis/shank tracking did impact the magnitude (Table F.1) and direction of the joint angles (Figure F.1); substantial differences (~ 9 degrees) were noted in the maximum and minimum joint motion in comparison to the thigh-fixed method.

Table F.1. The maximum, minimum and between-LSM variation (2SD) observed across the 20 LSMs for right knee flexion/extension, abduction/adduction and internal/external rotation angles. Data are presented for methods A, B and C and represent the mean (SD) of the same 6 jump trials.

	Flexion/Extension (°)			Abduction/Adduction (°)			Internal/External Rotation (°)		
Variable	A (DL/PS)	B (DL/TH)	C (FJ/TH)	A (DL/PS)	B (DL/TH)	C (FJ/TH)	A (DL/PS)	B (DL/TH)	C (FJ/TH)
2 SD	2.4 (0.1)	2.4 (0.5)	0.0 (0.0)	8.0 (0.0)	8.0 (0.0)	0.0 (0.0)	6.7 (0.4)	6.1 (0.5)	0.1 (0.0)
Max	5.7 (0.7)	6.0 (0.7)	5.2 (0.7)	8.0 (0.5)	7.6 (6.7)	5.9 (8.8)	6.8 (1.3)	7.5 (4.0)	3.8 (4.6)
Min	-103.5 (2.7)	-98.9 (3.7)	-99.6 (4.3)	-4.0 (0.5)	-7.1 (6.0)	-10.0 (4.4)	-6.7 (0.9)	-15.4 (9.8)	-15.5 (9.4)

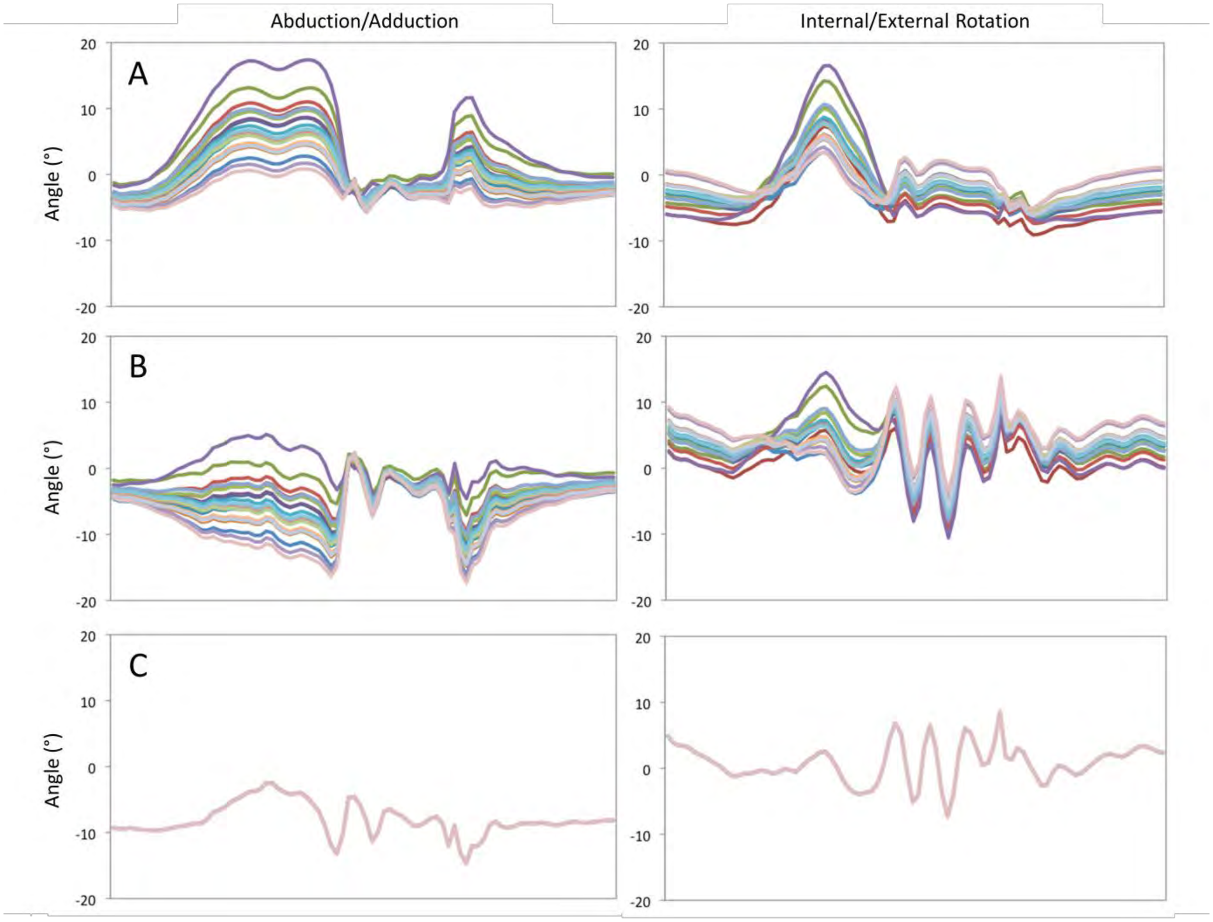


Figure F.1. Knee abduction/adduction and internal/external rotation described using methods A (pelvis and shank coordinate landmarks), B (a rigid marker cluster fixed to the thigh) and C (a rigid marker cluster fixed to the thigh and "functional" joints).

E.3. CONCLUSION

Tracking the thigh with its adjacent segments minimizes the influence of potential motion artifact and may therefore help to provide a better estimation of the actual knee joint motion. However, this approach has no impact on the between-day variation introduced during the LSM design process, which implies that the interpretation of any between-day changes in a kinematic variable should still be made with caution. To facilitate comparisons of this nature it is recommended that LSMs be created using functionally defined segment endpoints and tracked using landmarks defined in the pelvis and shank coordinate systems.

Appendix G

INFORMATION LETTER ONE

EXAMINING THE RELATIONSHIP BETWEEN FIREFIGHTER-SPECIFIC FITNESS AND WHOLE-BODY MOVEMENT PATTERNS

G.1. PURPOSE OF THE STUDY

Given the physical demands of firefighting general fitness (e.g. strength, endurance, aerobic capacity) is often viewed as critical to one's preparedness. In fact, most departments now include a Candidate Physical Ability Test (CPAT) to assess job-relevant fitness prior to hiring new recruits. However, firefighters still become injured and in many situations the injuries incurred are the direct result of efforts to become better physically prepared. Fitness is essential for safe and effective firefighting, but arguably more important is the way each individual moves while performing a task. In this project, an attempt will be made to establish a relationship between CPAT performance and whole-body movement patterns so that effective evidence-based injury prevention and performance enhancing strategies can be developed for the fire service.

G.2. PROCEDURES INVOLVED IN THIS STUDY AND TIME COMMITMENT

As a participant in this research study, you will be asked to attend three separate testing sessions at the University of Waterloo. In the first testing session, you will be asked to perform a series of low-effort whole-body movements (i.e. the Functional Movement Screen, FMS) while researchers video record your performance, and the firefighter Candidate Physical Ability Test (CPAT). In the second and third testing sessions, you will be asked to perform twenty-five repetitions of four simulated firefighting tasks (two lifts, hose drag and forcible entry) while your motion patterns are monitored. Each testing session will take between 1.5 and 2.5 hours of your time (including orientation and preparation). You will be asked to bring a pair of shorts, running shoes and a t-shirt to wear throughout testing. The data collection procedures are as follows.

Day 1

- Upon your arrival, you will be asked to perform 7 whole-body movements (i.e. Functional Movement Screen) so that we can examine the way you move. For example, you will be asked to perform a bodyweight squat, lunge and push-up. This information is confidential, and your name will not be associated with your scores (a random code will be assigned to your data set). If at any point you no longer wish to perform whole-body movements, please inform the researcher that you no longer wish to participate in the study.
- Upon completing the FMS, you will be familiarized with the CPAT and provided with an opportunity to practice the various events. It is a timed event and will be administered in a similar fashion to the official test. You will be required to wear a weighted vest (22.7 kg) to mimic the mass of a Self-Contained Breathing Apparatus.

Day 2 and 3

- Motion tracking markers will be taped to your skin overlying all major body segments (head, trunk, arms, and legs). Special position sensors will track these markers so that your movement patterns can be measured while you perform each task. After markers are applied, you will be asked to perform several standardized motions (leg and arm swings) to ensure that markers are visible and are not obstructing your movement.
- Following the application of the instrumentation, you will be asked to perform twenty-five repetitions of four different movements. As stated above, this information is confidential, and your name will not be associated with your scores (the same random code will be assigned to your data set). If at any point you no longer wish to perform

whole-body movements, please inform the researcher that you no longer wish to participate in the study. The four tasks will be:

  - Hose drag – You will be asked to place a thick rope over your right shoulder and walk forwards to simulate dragging a hose.
  - Forcible entry – You will be asked to strike a waist-level target with a 4.5 kg (10 lb) sledgehammer.
  - Light Box Lift – You will be asked to lift a 6.8 kg (15 lb) box to waist height and return to the ground.
  - Heavy Box Lift – You will be asked to lift an 18.2 kg (40 lb) box to waist height and return to the ground.

- Day 2 and 3 will be almost identical so that we can examine the between-day reliability of your performance. Again, if at any point you wish to discontinue testing, please inform the researcher that you no longer wish to participate in the study.
- Also, with your permission, pictures may be taken during testing.

G.3. POTENTIAL RISKS AND ASSOCIATED SAFEGUARDS

- There is always a risk of developing discomfort or soreness in muscles or joints when performing tasks such as those that will be performed in this study. The soreness may last for a day or two if you are not accustomed to this type of work. If the pain persists for more than 3 days, please contact the investigators.
- Some participants may experience mild skin irritation/redness from the tape used to attach the instrumentation to the skin. This is similar to the irritation that may be caused by a bandage and typically fades within 1-3 days.
- The portable parts of the electrical recording systems are battery operated and isolate you from the main power lines. There is no risk of electrical shock.
- You may discontinue at any time without penalty, especially if you are experiencing fatigue or discomfort (see below).

G.4. CHANGING YOUR MIND ABOUT PARTICIPATION

You may withdraw from the study at any time without penalty. To do so, indicate this to the investigators by saying, “I no longer wish to participate in this study”.

G.5. POTENTIAL BENEFITS OF PARTICIPATION

By participating in this study, you will have the opportunity to gain or further your knowledge and understanding of experimental procedures and theories in human movement research. Along with this information, you will be provided with on-site verbal feedback, following the third session, to reduce your risk of low-back injury and/or to enhance your physical performance if you wish. The knowledge gained from this research may aid in the prevention of injuries for firefighters.

G.6. REMUNERATION

Once testing has been completed you will also receive $100 ($33.33 per session) as a token of our appreciation for your participation in this project. There is no penalty to withdraw from this study at any time; however you will only be paid for each session completed. Please note that this amount received is taxable and it is your responsibility to report this amount for income tax purposes.

G.7. CONFIDENTIALITY AND SECURITY OF DATA

Each participant will be assigned an individualized 3-letter identification code. Only the investigators will have access to this code. All data will be stored indefinitely on computer hard drives (password protected) and/or digital storage media (locked in a filing cabinet in the investigator’s office). A separate consent will be requested in order to use photographs for teaching, for scientific presentations, or in publications of this work. When pictures are used facial images will be blurred or blacked out.

G.8. HEALTH SCREENING AND SUITABILITY FOR PARTICIPATION

This questionnaire asks some questions about your health status. This information is used to guide us with your entry into the study. Due to the physical demands of this protocol, only those who have no previous health issues may participate in this study.

G.9. CONCERNS ABOUT PARTICIPATION

We would like to assure you that this study has been reviewed by, and received ethics clearance through, the University of Waterloo's Office of Research Ethics (ORE). However, the final decision about participation is yours, and your decision to participate, refuse participation, or withdraw from the study will not have a negative impact on your relationship with your employer. In the event you have any comments or concerns resulting from your participation in this study, please contact Dr. Susan Sykes (Director ORE) by telephone at (519) 888-4567 ext. 36005 or by e-mail (ssykes@uwaterloo.ca).

G.10. QUESTIONS ABOUT THE STUDY

If you have any further questions or want any other information about this study, please feel free to contact David Frost, Dr. Jack Callaghan, or Dr. Stuart McGill (contact information provided below).

Sincerely Yours,

David Frost, PhD Candidate
Dept. of Kinesiology
University of Waterloo
d3frost@uwaterloo.ca
519-888-4567 ext. 33865

Dr. Jack Callaghan
Dept. of Kinesiology
University of Waterloo
callagha@uwaterloo.ca
519-888-4567 ext. 37080

Dr. Stuart McGill
Dept. of Kinesiology
University of Waterloo
mcgill@uwaterloo.ca
519-888-4567 ext. 36761

CONSENT OF PARTICIPANT

By signing this consent form, you are not waiving your legal rights or releasing the investigator(s) or involved institution(s) from their legal and professional responsibilities.

I have read the information presented in the information letter about a study being conducted by David Frost (Student Investigator), Dr. Jack Callaghan (Faculty Supervisor) and Dr. Stuart McGill (Faculty Supervisor) of the Department of Kinesiology at the University of Waterloo. I have had the opportunity to ask any questions related to this study, to receive satisfactory answers to my questions, and any additional details I wanted. I am aware that I may withdraw from the study without penalty at any time by advising the researchers of this decision.

This project has been reviewed by, and received ethics clearance through, the University of Waterloo's Office of Research Ethics (ORE). I was informed that if I have any comments or concerns resulting from my participation in this study, I may contact Dr. Susan Sykes (Director, ORE) at (519) 888-4567 ext. 36005, or by email at ssykes@uwaterloo.ca.

With full knowledge of all foregoing, I agree, of my own free will, to participate in this study titled: "Examining the relationship between firefighter-specific fitness and whole-body movement patterns."

Participant's Name (Please Print): ______________________________

Participant's Signature: ______________________________

Dated at Waterloo, ON: ______________________________

Witnessed: ______________________________

CONSENT TO USE PHOTOGRAPHS or VIDEOS IN TEACHING, PRESENTATIONS, and/or PUBLICATIONS

Sometimes a certain photograph or video clearly demonstrates a particular feature or detail that would be helpful in teaching or when presenting the study results at a scientific conference or in a publication.

I agree to allow photographs or videos in which I appear to be used in teaching, scientific presentations and/or publications with the understanding that I will not be identified by name. I am aware that I may withdraw this consent at any time without penalty, and the photograph will be discarded. When pictures are used facial images will be blurred or blacked out.

I was informed that if I have any comments or concerns resulting from my participation in this study, I may contact Dr. Susan Sykes (Director, Office of Research Ethics) by telephone at (519) 888-4567 ext. 36005 or by e-mail (ssykes@uwaterloo.ca).

Participant's Name (Please Print): ______________________________

Participant's Signature: ______________________________

Dated at Waterloo, ON: ______________________________

Witnessed: ______________________________

Appendix H

INFORMATION LETTER TWO

CAN MOVEMENT- OR FITNESS-CENTRIC TRAINING PROGRAMS ALTER THE LOW BACK INJURY POTENTIAL OF FIREFIGHTERS?

H.1. PURPOSE OF THE STUDY

When performing their duties, firefighters have a high reporting rate of low-back injuries due to the physically demanding nature of their work. There is some indirect evidence to suggest that firefighters who have trouble controlling their normal body mechanics may be more susceptible to low-back injuries than firefighters who exhibit excellent body control. However, the effects of body control on the low-back injury potential of firefighters have not yet been tested directly. It is the purpose of this study to scientifically address this limitation in hopes that information gathered can be implemented in injury prevention training programs for firefighters.

H.2. PROCEDURES INVOLVED IN THIS STUDY AND TIME COMMITMENT

As a participant in this research project, you will be asked to attend a 20-minute movement testing eligibility assessment at Fire Station #1 (City of Pensacola). During this assessment, you will be asked to perform 10 standardized whole-body bodyweight movements while being videotaped. The movements consist of body-weight squats, lunges, step-ups, push-ups, general hip and shoulder stretches. You will be asked to wear shorts, athletic shoes, and a tight-fitting t-shirt. The information gathered during the assessment may provide insight into your potential for sustaining a work-related injury. This information will be shared amongst the research team, and your name will not be associated with your scores (a random code will be assigned to your data set). If at any point you no longer wish to perform the tasks, please inform the researcher that you no longer wish to participate in the study.

Following the movement testing session, and determination of your eligibility, you may be asked to participate in a 12-week exercise study if eligible. To be eligible, you must have experienced no pain during the movement assessment (described above) and you are willing to engage in a movement training program. If you are approached about participating in the exercise study, you will be asked to attend a 1-hour exercise session 3 times/week (for 12 weeks) at the Andrews Institute in Gulf Breeze (Athletes' Performance facility). All exercise sessions will be coached by Athletes' Performance staff and provided free of charge

If you are eligible and agree to participate in the 12-week exercise study, you will also be asked to attend two biomechanical testing sessions (pre- and post- 12-weeks of training) during which you will perform laboratory-simulated firefighting tasks while having your muscle and movement patterns monitored by University of Waterloo biomechanics researchers. The biomechanical testing sessions are separate from the exercise sessions, and data from these biomechanical testing sessions (i.e., measured muscle and movement patterns) will be used to determine if completing the exercise program has the ability to alter low-back injury potential. Each biomechanical testing session will take approximately 3.5 hours of your time (including orientation and preparation). No biomechanical measures will be made during the exercise sessions. The biomechanical data collection procedures are as follows.

- Upon your arrival, the skin overlying muscles of the back, abdominal region, buttocks, and thighs will be shaved and cleansed so that surface EMG electrodes can be taped to your skin. Two of the researchers, Tyson Beach and David Frost, will perform all shaving and electrode application. A disposable razor will be used and discarded after shaving. EMG will be collected throughout all of the procedures to document your muscle activity.

- You will be asked to perform a series of exercises that involve using your back, hip and knees, which will require your maximum effort. The exercises consist of basic back, hip, and knee bending motions (e.g., sit-ups). Information from these tests allows the researchers to compare your data against the data of other participants.
- In addition to the EMG electrodes, motion tracking markers will be taped to your skin overlying all major body segments (head, trunk, arms, and legs). These markers will be tracked by special position sensors to measure the movement of your body when you perform all tasks. After markers are applied, you will be asked to perform several standardized motions (leg and arm swings) to ensure that markers are visible and are not obstructing your movement.
- Following equipment set-up, you will be asked to perform the simulated firefighting tasks and whole-body movement patterns while we measure your body motions and muscle activities. Examples of the tasks that you will be asked to perform during the biomechanical testing sessions are included in Appendix I of this document (Page 6).
- Again, if at any point you wish to discontinue testing, please inform the researcher that you no longer wish to participate in the study.

H.3. POTENTIAL RISKS AND ASSOCIATED SAFEGUARDS

There is always a risk of developing discomfort or soreness in muscles or joints when performing tasks or exercises such as those that will be performed in this study. The soreness may last for a day or two if you are not accustomed to this type of work. If the pain persists for more than 3 days, please contact the investigators. Athletes' Performance staff will conduct pre-exercise screening tests to ensure that you will not engage in exercises that would put you at increased risk of pain or injury.

Maximal effort exercises of the back, abdominals, buttocks, and thighs will be performed in order to compare data between all participants measured during the performance of the tasks. Discomfort or soreness could result from these activities. However, these efforts are similar to those you might produce while during a typical exercise session.

Some participants may experience mild skin irritation/redness from the tape used to attach the instrumentation to the skin. This is similar to the irritation that may be caused by a bandage and typically fades within 1-3 days.

If you have an allergy or sensitivity to rubbing alcohol, please inform the investigators. Rubbing alcohol must be used to cleanse the skin prior to electrode attachment. As this is a mandatory step in the procedure, you will not be able to participate in the study if you have an allergy or sensitivity to rubbing alcohol.

The portable parts of the electrical recording systems are battery operated and isolate you from the main power lines. There is no risk of electrical shock.

H.4. CHANGING YOUR MIND ABOUT PARTICIPATION

You may withdraw from the study at any time without penalty. To do so, indicate this to the investigators by saying, “I no longer wish to participate in this study”.

H.5. POTENTIAL BENEFITS OF PARTICIPATION

As a participant in this study, you will receive a personalized exercise program one month following your movement assessment. The exercise program will be designed to help you improve your movement patterns.

The knowledge gained from this research may aid in the prevention of low-back injuries in firefighters.

H.6. CONFIDENTIALITY AND SECURITY OF DATA

Each participant will be assigned an individualized 3-letter identification code. Only the investigators will have access to this code. All data will be stored indefinitely on computer hard drives (password protected) and/or digital storage media (locked in a filing cabinet in the investigator’s office). Only University of Waterloo researchers will have access to the data. A separate consent will be requested in order to use photographs for teaching, for scientific presentations, or in publications of this work.

H.7. MEDICAL SCREENING AND ELIGIBILITY FOR PARTICIPATION

A “Current Health Status Form” asks some questions about your health status. This information is used to guide us with your entry into the study. Due to the physical demands of this protocol, only those who have no previous health issues (e.g., cardiovascular, neurological, metabolic, or musculoskeletal disorders) may volunteer for this study.

H.8. CONCERNS ABOUT PARTICIPATION

We would like to assure you that this study has been reviewed by, and received ethics clearance through, the University of Waterloo's Office of Research Ethics (ORE). However, the final decision about participation is yours, and your decision to participate, refuse participation, or withdraw from the study will not have a negative impact on your relationship with your employer. In the event you have any comments or concerns resulting from your participation in this study, please contact Dr. Susan Sykes (Director ORE) by telephone at (519) 888-4567 ext. 36005 or by e-mail (ssykes@uwaterloo.ca).

H.9. QUESTIONS ABOUT THE STUDY

If you have any further questions or want any other information about this study, please feel free to contact Tyson Beach, David Frost, Dr. Jack Callaghan, or Dr. Stuart McGill (contact information provided below).

Sincerely Yours,

Tyson Beach, PhD Candidate
Dept. of Kinesiology
University of Waterloo
tbeach@uwaterloo.ca
519-888-4567, ext. 37576

David Frost, PhD Student
Dept. of Kinesiology
University of Waterloo
d3frost@uwaterloo.ca
519-888-4567, ext. 33865

Dr. Jack Callaghan
Dept. of Kinesiology
University of Waterloo
callagha@uwaterloo.ca
519-888-4567 ext. 37080

Dr. Stuart McGill
Dept. of Kinesiology
University of Waterloo
mcgill@uwaterloo.ca
519-888-4567 ext. 36761

CONSENT OF PARTICIPANT

I have read the information presented in the information letter about a study being conducted by Tyson Beach, David Frost, Dr. Jack Callaghan, and Dr. Stuart McGill of the Department of Kinesiology at the University of Waterloo. I have had the opportunity to ask any questions related to this study, to receive satisfactory answers to my questions, and any additional details I wanted. I am aware that I may withdraw from the study without penalty at any time by advising the researchers of this decision.

This project has been reviewed by, and received ethics clearance through, the University of Waterloo's Office of Research Ethics (ORE). I was informed that if I have any comments or concerns resulting from my participation in this study, I may contact Dr. Susan Sykes (Director, ORE) by telephone at (519) 888-4567 ext. 36005 or by e-mail (ssykes@uwaterloo.ca).

With full knowledge of all foregoing, I agree, of my own free will, to participate in this study.

Participant's Name (Please Print): ______________________________

Participant's Signature: ______________________________

Dated at Gulf Breeze, FL: ______________________________

Witnessed: ______________________________

CONSENT TO USE PHOTOGRAPHS or VIDEOS IN TEACHING, PRESENTATIONS, and/or PUBLICATIONS

Sometimes a certain photograph or video clearly demonstrates a particular feature or detail that would be helpful in teaching or when presenting the study results at a scientific conference or in a publication.

I agree to allow photographs or videos in which I appear to be used in teaching, scientific presentations and/or publications with the understanding that I will not be identified by name. I am aware that I may withdraw this consent at any time without penalty, and the photograph will be discarded.

I was informed that if I have any comments or concerns resulting from my participation in this study, I may contact Dr. Susan Sykes (Director, Office of Research Ethics) by telephone at (519) 888-4567 ext. 36005 or by e-mail (ssykes@uwaterloo.ca).

Participant's Name (Please Print): ________________________________

Participant's Signature: ________________________________

Dated at Gulf Breeze, FL: ________________________________

Witnessed: ________________________________