Factors Contributing to Ladder Falls and Broader Impacts on Safety and Biomechanics

by

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Ladder falls cause disabling injury and death in the workplace and at home. Numerous scenarios lead to ladder falls given the variation in ladder types and how they are used. Of the potential factors influencing ladder fall risk under these different scenarios, many have yet to be investigated. This dissertation used a multifaceted approach to determine ladder fall risk factors. Specifically, this dissertation tested younger and older adults, designed occupational and domestic based ladder experiments, and investigated factors that precede and follow a ladder falling event. Aim 1 of this dissertation identified individual factors associated with safe and effective domestic ladder use among older adults. Balance measured with clinical assessments was a primary predictor of safe and effective ladder use. Aim 2 of this dissertation determined individual, environmental and biomechanical factors that aid in arresting a falling event from a ladder. Ascending climbs, males, greater upper body strength, higher hand placement during recovery and reestablishing at least one foot back onto the ladder during recovery were associated with reduced ladder fall severity (i.e. better recovery). Surprisingly, glove condition was not found to contribute to ladder fall severity. Hand-rung forces were correlated with the severity of the falling event and not an individual's ability to generate force, suggesting that these forces are dependent on the circumstances of the perturbation. Findings from this dissertation may guide fall interventions (e.g. screenings, improvements in safety standards, perturbation response training, ladder re-design). Therefore, this work is expected to have impact on the safety field by reducing ladder fall injuries. Furthermore, this work contributes new knowledge to the biomechanics of ladder use and fall

recovery. As part of a larger strategy to improve safety for all populations, increased diversity is needed in the Science, Technology, Engineering, and Mathematics (STEM) fields. Aim 3 of this dissertation utilized biomechanics as a link to develop a student-interest based pedagogy to improve engagement of underrepresented groups in the STEM fields. This work found lectures tailored to student interests to increase student engagement. Long-term effects from this work can increase diversity in the STEM fields including safety.

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Preface

I would like to recognize the remarkable individuals who have supported and advanced my professional and research achievements. Thank you to my committee members, Kurt Beschorner, Stephen Lord, Arash Mahboobin, Alison Novak and Mark Redfern for their mentorship and contributing knowledge to the content in this dissertation. Each mentor was instrumental to my growth as an academic. Arash Mahboobin expanded my insight on the Scholarship of Teaching and Learning. Alison Novak challenged my perspective beyond that of an engineer. Mark Redfern enhanced my critical thinking skills to question more. I would like to extend my sincere gratitude to my advisors who have been the strongest advocates in my career. My co-advisor, Stephen Lord, oversaw part of my research training, increasing my proficiency in research design and knowledge of critical individual-based fall risk factors. My advisor, Kurt Beschorner, has guided my research career for 8 years, providing constructive feedback and wholehearted advice. He has been essential to my success and ambition to pursue research. This work would not have been possible without the help from colleagues at Human Movement and Balance Laboratory at the University of Pittsburgh; Falls, Balance and Injury Research Centre at Neuroscience Research Australia; and Gait Analysis and Biodynamics Laboratory at the University of Wisconsin-Milwaukee. Thank you to my friends far and near that have supported and advised me through the successes and challenging times. Thank you to my family. You have supported my research and travels, even when they interfered with holidays and Packer games. Finally, thank you to Gerald Ferrer for his unconditional support through this journey.

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1.0 Introduction

1.1 Preamble

Ladder falls are a frequent and severe source of injuries in the workplace. Previous ladder fall research has primarily focused on occupational falls, which ignores the breadth of the problem. Ladder fall injuries are also common in the domestic setting and among older adults (i.e. retirement age or older). While certain environmental changes (ladder setup and design) have been suggested to prevent ladder falls, there is a lack of knowledge on *individual factors* that influence ladder use and fall risk. Furthermore, the majority of ladder fall research aims to mitigate factors that initiate a falling event. The influence of individual and environmental factors and the biomechanical responses *after a climbing perturbation* are not well understood. Therefore, <u>the goal of this dissertation is to determine individual factors that influence task performance on a ladder as well as individual, environmental and biomechanical response factors that contribute to arresting a ladder fall</u>. The *innovation* in this dissertation stems from the multifaceted approach to determine ladder fall risk factors. Specifically, this dissertation includes testing among younger and older adults, occupational and domestic-based ladder experiments, and investigates factors that precede and follow a ladder falling event. Knowledge from this dissertation will advance the *long-term goal* of reducing ladder fall injuries by targeting a diverse range of ladder falling events. To achieve this goal, this dissertation will complete the following two aims.

Aim 1: To determine individual factors that influence task performance on a ladder.

Younger and older adults changed a light bulb on a household stepladder. Task performance was quantified through task completion time and standing stability (i.e. measured via center of pressure) on the stepladder. Individual factors were measured from physiological, cognitive and psychological assessments. The relationship between individual factors and task performance was investigated. In addition, the implication of individual factors on ladder fall risk is discussed.

Aim 2: To determine the influence of individual and environmental factors on ladder fall severity and the biomechanical responses after a ladder climbing perturbation.

Participants climbed a vertically fixed ladder across three glove conditions (bare hands, low friction, high friction). A misstep perturbation was simulated below the foot during both climbing directions and different glove conditions. The ladder was instrumented to measure kinetics of the hands and the safety harness. Reflective markers (captured by a motion capture system) measured the kinematic response of the body. The influence of climbing direction, glove use, gender and upper body strength on fall severity was investigated. Biomechanical responses after the climbing perturbation from the upper and lower body were quantified and assessed with fall severity.

Outcomes from this dissertation and other research projects are influenced by the study design, which is determined by the perspectives of the investigators. Perspectives stems from one's individual background and experiences (e.g. gender, ethnicity, education). Poor representation of women and minorities in the engineering fields including safety topics, limits the diversity of viewpoints to solve problems. This has a negative impact on the applicability of research to different populations. To improve the quality of safety research, there is a need to increase diversity in the Science, Technology, Engineering and Mathematics (STEM) fields. Relating engineering concepts to student-interests' may be a useful pedagogy and steppingstone to improve engagement of underrepresented persons in STEM. The third aim of this dissertation focuses on improving diversity in STEM by investigating the effects of student-specific content on engagement.

Aim 3: To quantify the impact of student-specific content on improving student engagement in a biomechanics outreach program.

Two groups of 10^{th} grade students underrepresented in STEM participated in a 5-week program with biomechanics workshops delivering the same content. One group received content tailored to their interests and were assessed on engagement. Both groups were assessed on performance. The effects of interest-tailored lectures on student engagement and performance was investigated.

This dissertation identifies characteristics of safe and effective ladder use and factors that aid in arresting a falling event from a ladder. Knowledge gained from this dissertation is necessary to develop ladder fall interventions (e.g. screenings, improvements in safety standards, perturbation response training, ladder re-design) across multiple settings. Thus, this work is expected to have high societal impact by reducing ladder fall injuries. Furthermore, this dissertation develops a student-interest based pedagogy to improve engagement of underrepresented groups in the STEM fields. Long-term effects from this work can increase diversity in the STEM fields to improve the applicability of safety research.

1.2 Framework

This dissertation utilized the human factors approach to investigate contributing factors of ladder falls. Specifically, this dissertation investigates the individual, environmental and interface between the individual and environment on ladder fall risk. In this dissertation, the studied interface between the individual and environmental are biomechanical factors (Figure 1.2.1).

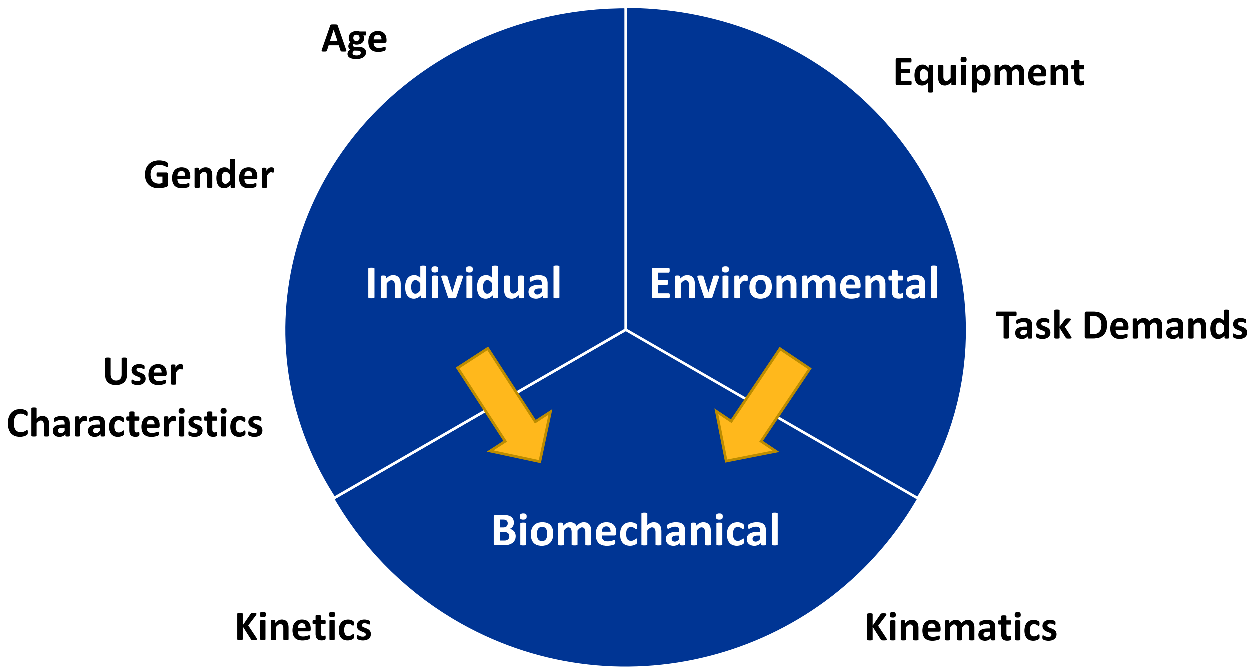


Figure 1.2.1: The human factors approach. The human factors approach investigates the individual, environment, and the interface between the individual and environment. The interface of interest in this dissertation are biomechanical factors. Specifically, this dissertation investigates age, gender, and user characteristics for individual factors; equipment and task demands for environmental factors; and kinetics and kinematics for biomechanical factors.

Furthermore, this dissertation investigates the link between student interests and engagement in STEM. Each aim in this dissertation corresponds to a set of predictors, an experiment and outcome measures (Figure 1.2.2).

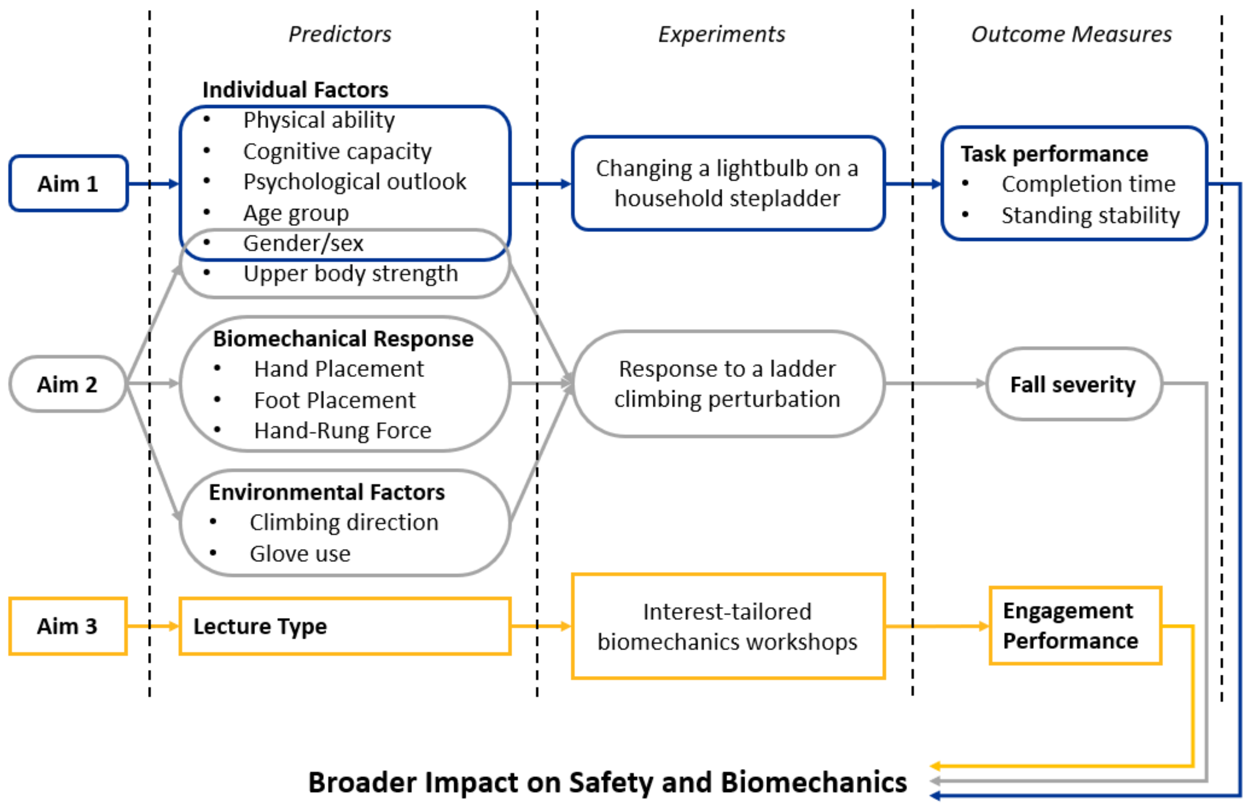


Figure 1.2.2: Predictors, experiments, and outcome measures by aim.

This dissertation begins with background on epidemiology of ladder falls, ladder experiments, needed diversity in safety, and links to STEM engagement. Specific background knowledge on ladder falls and student engagement will be provided prior to chapters corresponding to each aim. Aim focused chapters consist of one to three studies (or sections). This dissertation closes with conclusions and final remarks. The primary chapters of this dissertation are outlined as followed.

Background

Characterizing User-specific Factors of Ladder Fall Risk (Aim1)

Individual, Environmental and Biomechanical Response Factors on Fall Recovery after a Ladder Climbing Perturbation (Aim 2)

Impact of Student-specific Content on Improving Student Engagement in a Biomechanics Outreach Program (Aim 3)

Conclusion and Final Remarks

2.0 Background

2.1 Falls

Falls are a leading cause of disabling injuries [1] and unintentional fatalities [2]. Falls account for over a quarter (26.3%) of emergency department visits related to injury, poisoning and adverse events [3]. This is nearly 3 times the amount of emergency department visits due to the next leading cause from an unintentional injury by motor vehicle traffic (8.9%) [3]. Not only are fall injuries frequent, they are severe. Falls lead in non-fatal injury costs from emergency department visits, contributing to 41% of hospitalized and 30% of treated and released injury costs [4]. Alarmingly, fatal and non-fatal injury costs from falls were estimated to be $175 billion in 2013 (Figure 2.1.1.a) [4, 5].

The severity of a fall injury can also lead to death. Falls are ranked 3rd in causes for unintentional injury deaths and the leading cause of unintentional injury deaths among older adults (aged 65^{+} years) in the US [2]. Concerningly, the rate of older adult deaths from falls is growing. Between 2007 and 2016, the rate of older adult deaths from falls increased 31% (3.0% per year), leading to an incidents rate of 61.6 per 100,000 US residents in 2016 [6]. This trend is seen in several counties and falls among older adults is recognized as a global problem by the World Health Organization [7]. Some public health officials have deemed this issue to be an emerging epidemic [8, 9]. With a globally aging population, the magnitude of this problem is estimated to increase by a factor of 2.3 by 2050 [10]. This will result in an additional 393 million falls and $1.2 trillion (not estimating for cost inflation) by 2050 [11] in adults older than 60 years of age.

Falls are also a problem among the working population. In the occupational setting, falls are the leading cause of a disabling injury, accounting for 27% and $13.7 billion of workers compensation costs [1]. Overexertion and repetitive motion are other common causes to workplace injuries, but the costs of these injuries have decreased a combined total of one billion dollars between 1998 and 2009 [1]. Decreases in costs for overexertion and repetitive motion injuries are likely the result of a greater understanding of risk factors associated with these injuries, that have led to many injury prevention paradigms (i.e. revised NIOSH lifting equation [12], strain index [13], and RULA [14]). Thus, ergonomists, biomechanists and tribologists are motivated to understand mechanisms of workplace falls. Today, the majority of occupational fall research has focused on slips and trips during gait [15-23]. These studies investigated mechanisms of same-level falls, but many of the falls resulting in the most severe injuries occur from a height.

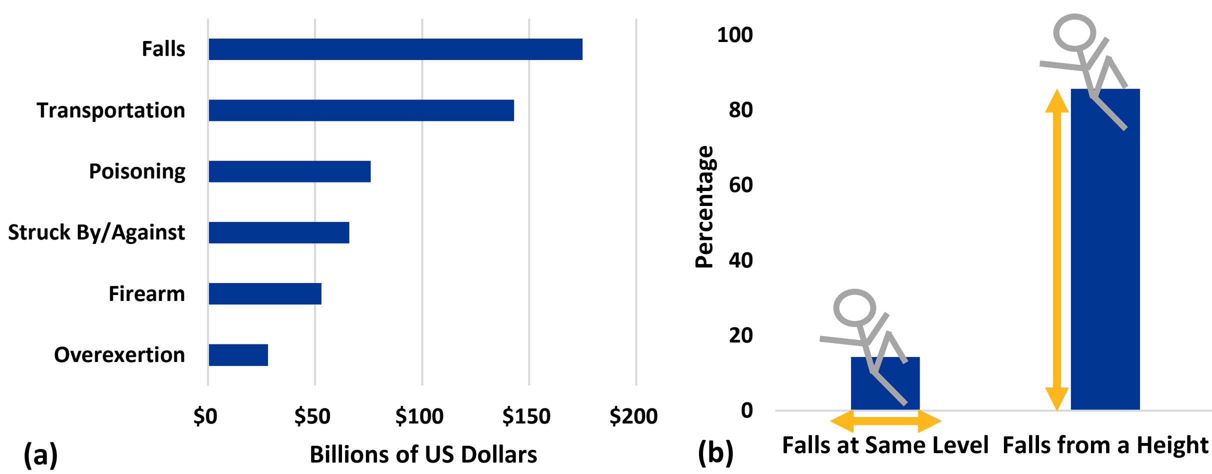


Figure 2.1.1: Fall costs and percentages by fall level. Nationally estimated costs for fatal and non-fatal injuries treated in US emergency departments in 2013 (a). Data extracted from [4, 5]. Percentage of fatal falls at the same level and from a height (b). Data extracted from [24].

Falls from a height are understudied. This is surprising, given the majority of occupational fatal falls are from a height (Figure 2.1.1.b) [24]. Furthermore, fatal falls from a height have increased 26% between 2011 and 2016 [25], with the plurality of these injuries occurring from a ladder (Figure 2.1.2) [25, 26]. Ladder falls are of high concern in the mining [27, 28] and construction [29, 30] industries. In particular, ladders account for the plurality (20%) of tool and equipment non-fatal injuries in construction [29]. Ladder falls are also frequent incidents in the domestic setting [31-36] with incidence rates highest among older adults (i.e. retirement age or older) [32]. Therefore, ladders are a key contributor to the global falls problem.

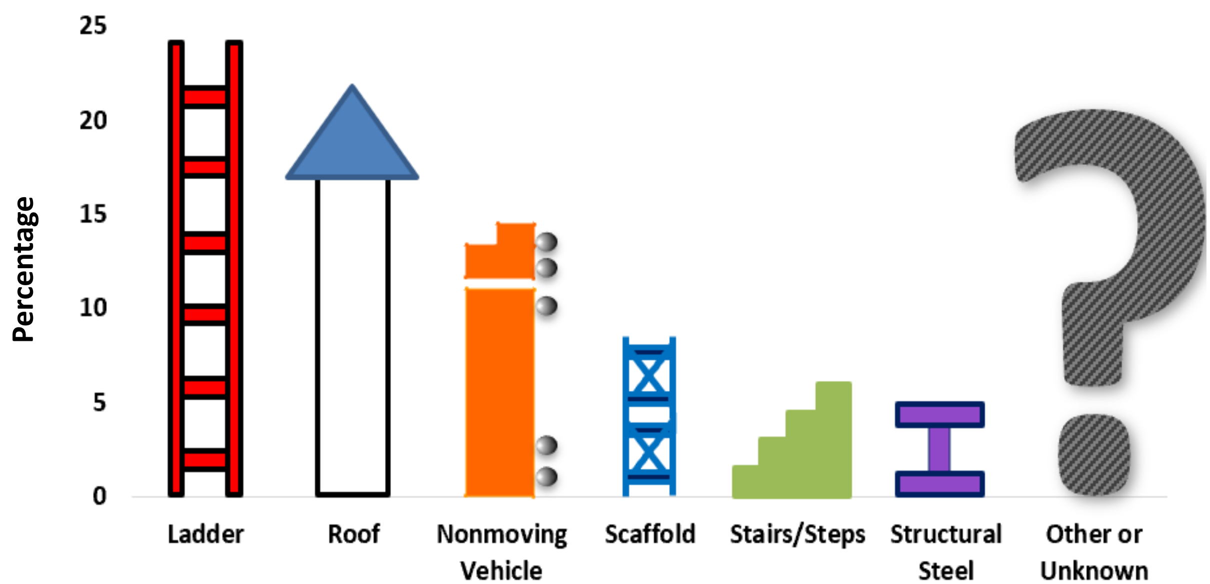


Figure 2.1.2: Fatal falls from a height. The percentage of fatal falls by elevation: ladder, roof, non-moving vehicle, scaffold, stairs/steps, structural steel, other/unknown. Data extracted from [26].

2.2 Epidemiology of Ladder Falls

Findings from epidemiology studies on ladder falls is summarized below with key studies highlighted in Table 2.2.1. To summarize the findings, terminology in the literature was consolidated. Nomenclature used in this dissertation and the associated terminology in the literature is defined in Appendix A.1.

2.2.1 Population

Multiple countries (Australia, Denmark, Finland, Spain, Sweden, UK, US) have stressed concern for adverse ladder events [31-35, 37, 38], and nearly all of these events occur from a fall (88%-96%) [39, 40]. The majority of ladder fall incidents occur among males (72%-95%) [28, 31, 32, 34-36, 39, 41, 42], but females are also susceptible to experiencing a ladder fall (5%-28%), particularly while using a stepladder indoors [41]. While more studies have been focused on occupational ladder falls [27, 28, 30, 37-40, 42-46], some studies have reported more ladder fall injury cases in the domestic setting (61%-83%) compared to the occupational setting (17%-39%) [31-36]. The mean age of the ladder user at the time of fall or ladder-related injury in these studies ranged between 39 and 58 years old. The youngest and oldest victims of these studies were a 1-month old and 101 years old, respectively [34]. Furthermore, victims were younger in the occupational setting (mean age between 39 and 48 years old) than in the domestic setting (mean age between 50 and 62 years old).

An estimated 136,118 US citizens are treated for ladder-related injuries each year, averaging to 49.5 per 100,000 inhabitants [34]. This study found incidents rates to be highest in the 36-45 year old age group (occupational-related injuries included), while another study found non-occupational fall from ladder and scaffold incidence rates to be highest among older adults (aged 65-69 years old) [32]. Incidence rates in the domestic setting have been reported to be 0.7 to 0.8 per 1,000 inhabitants [32, 35], with higher incidence rates among males (1.18 per 1,000 inhabitants) than females (0.41 per 1,000 inhabitants) [32]. In the occupational setting, incidence rates per full-time employee (FTE) for ladder fall fatalities was 0.09 per 100,000 FTE [42], this equates to an estimated 116 ladder deaths in the US for 2018 (based off the US 2018 full-time employee population of 128.57 million [47]). Interestingly, occupational incidence rates were higher in non-fatal injuries treated in the emergency department (2.6 per 10,000 FTE) than non-fatal injuries reported by employers (1.2 per 10,000 FTE) [42]. The construction industry leads in incidence rates and injuries from adverse ladder events (23%-57%), but high percentages of adverse ladder events have also been reported in the manufacturing (8%-25%), retail (10%-21%), and service (3%-34%) industries [38-40, 42, 45, 46].

Ladder falls are likely contributing to the increases in adverse fall events. From 1990 to 2005, the number of ladder-related injuries increased by over 50%, increasing incidence rates of those treated in emergency departments by nearly 27% [34]. Another study found admissions into level 1 trauma services for ladder falls to increase from 3.01% to 4.17% over a 5-year period (2007 to 2011), with incidence risk of intensive care unit (ICU) admissions to increase from 0.27% to 0.40% [31]. Thus, the rate of ladder falls is increasing.

2.2.2 Ladder use

Ladder falls and injuries commonly occur from three types of ladders: stepladder, straight ladder and fixed ladder (Figure 2.2.1). While ladder type can be more specific than stepladder, straight and fixed, the following nomenclature was used to consolidate terminology in the literature

(Appendix A.1). Guidelines from the American Ladder Institute assisted in formulating this dissertation's definition for a ladder and definitions for a stepladder, straight and fixed ladder [48].

Ladder: a device instrumented with steps, rungs or cleats to enable a person to ascend or descend to different elevation levels.

Straight ladder: a portable ladder that is either non-adjustable in length (single section) or adjustable in length by multiple sections with articulated joints that extend the sections in line with each other.

Stepladder: a portable ladder with flat steps and a hinged based.

Fixed ladder: a ladder that is fixed to the ground, wall or surface.

Figure 2.2.1: Ladder type. Examples of stepladders (a, b), straight ladders (c, d) and fixed ladders (e, f). Specifically depicted are a household stepladder (a), A-frame ladder (b), single ladder (c), extension ladder (d), ladder fixed to a wall (e) and a ladder fixed to a moving vehicle (f).

Most adverse ladder events occurred from portable ladders (straight and stepladders). The range of reported ladder falls and injuries was 6% to 57% for stepladders, 30% to 89% for straight ladders, and 1% to 25% for fixed ladders [30, 35-37, 40, 43, 44, 46]. Other ladders involved in a small number of injuries were multipurpose, platform, rolling/wheeled, trestle, job-made, aerial, fruit picker, storeroom and substitute (e.g. chair) ladders. One study found the majority of males to fall from straight ladders (63%) and the majority of females to fall from stepladders (56%) [41]. In the domestic setting, ladder-related cases were typically most common among straight ladders (35%-77%), followed by stepladder (16%-45%) and fixed ladders (1%-8%) [35, 36]. In the occupational setting, ladder-related cases were more variable among straight ladders (19%-89%), stepladder (6%-57%) and fixed ladders (1%-25%) [30, 35-37, 40, 43, 44].

Ladder-injury cases typically occur outside in the domestic setting (63%-77%) and inside in the occupational setting (70%) [35, 41]. However, in the home setting, ladder falls among females are typically indoors (54%) [41]. Most ladder-injury cases have been reported to occur in the warmer months. Specifically, 32% of admissions for level 1 trauma from ladder falls occurred between November and January in Australia [31], 58% of ladder-related injuries occurred between April and September in Sweden [35], and 47% of ladder and scaffold falls occurred between June and September in Denmark [32]. Ladder-related injuries can occur any day of the week, but one study found more to occur on the weekends in the domestic setting [36], and there is no consensus among days of the week where ladder injuries occur in the occupational setting [35, 36, 45]. In addition, more occupational ladder falls were found to occur in the morning or prior to breaks, potentially indicating fatigue and attentiveness to be contributing factors [43, 45].

Ladders are used to climb to or complete a task at a different level of elevation. At the time of fall/injury, ladder users were either standing/working (32%-66%), ascending (11%-34%) or descending (19%-28%) [28, 30, 36, 37, 40, 41, 43, 46]. Across the domestic and occupational settings, the most common activity for ladder use prior to the fall/injury was maintenance/repair or painting (14%-46%) [28, 30, 31, 33, 35, 37, 41, 46]. Other common activities for ladder use prior to fall/injury were construction (1%-32%), production and transport (3%-16%), removing snow from the roof (14%), getting an object from the attic (8%-12%), garden/yard pruning (2%-12%), gutter cleaning (3%-12%), decorating (9%) and cleaning house/windows (3%-7%) [28, 30, 31, 33, 35, 37, 41, 46].

Heights of ladder falls were found to range between 0.2 m and 78 m [30-33, 35, 37, 40-42, 46]. In the occupational setting, one study found heights between 1.8 m and 3 m to be the most common cause of fatality (28%) [42], while another study found the majority (67%) of fall fatalities to occur at heights greater than 3 m [40]. However, ladder fall fatalities have been reported to occur at heights lower than 0.6 m [42]. Domestic ladder falls appear to occur at lower heights with the majority occurring at heights greater than 1 m (66%), but a substantive proportion occurring at heights less than 1 m (31%) [32].

2.2.3 Cause of fall

Ladder falls can be broadly categorized into two types of falls. That is, a fall *from* the ladder or a fall *with* the ladder [44]. A fall *with* the ladder occurs when the ladder becomes unstable, causing the ladder to fall while the climber is on the ladder. A fall *from* the ladder occurs when the climber's hands and feet decouple from the ladder, causing them to fall off the ladder (Figure 2.2.2).

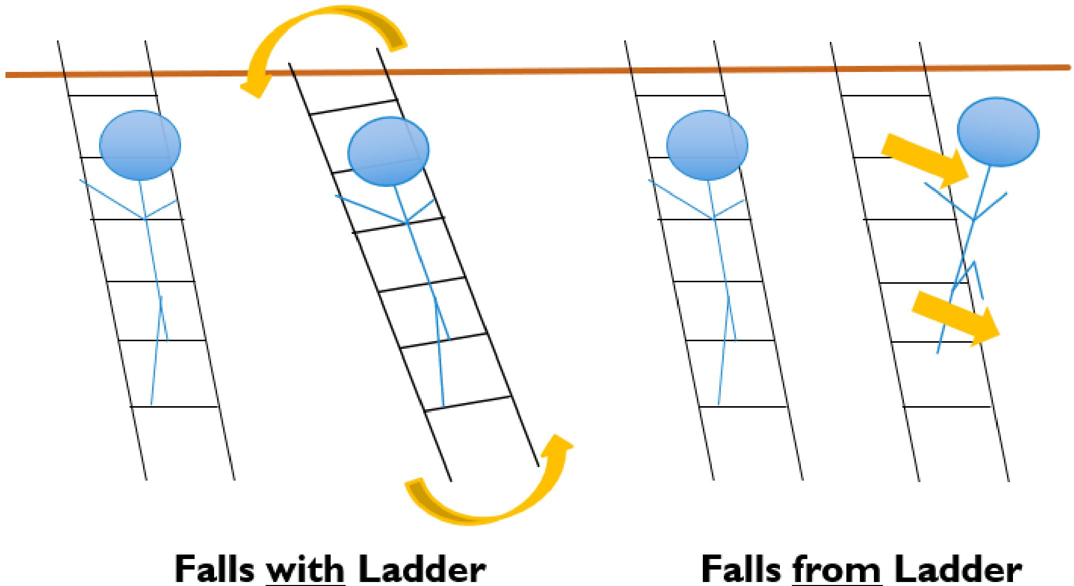


Figure 2.2.2: Ladder fall type. A fall with the ladder (left) and a fall from a ladder (right).

Common causes to falls with ladders are due to the ladder tipping and slipping. Falls from ladders are commonly caused by a climber slip, misstep or loss of balance. Across all ladder falls, ladder tipping or slipping (19%-71%) and a climber slip, misstep or lost balance (9%-40%) cause most falls [28, 33, 35-37, 39, 41, 43, 44, 46]. Studies that broke down these causes found a ladder slip (typically at the ladder base, 19%-38%) to be more frequent than a ladder tip (typically movement at the top of the ladder, 4%-19%) [30, 35, 37, 44], and the breakdown across a climber slip (14%-15%), misstep (4%-10%) and lost balance (1%-19%) to be similar [28, 30, 36, 41, 43].

Overall, ladder tipping or slipping and climber slip, misstep or lost balance can be classified as the general ladder fall causes. Other defined causes of ladder falls that would lead to the ladder tipping/slipping or a climber slip/misstep/lost balance are overreaching (4%-19%), transitioning (6%-22%), external force or object interference (2%-15%), improper setup/use (2%-13%), unstable surface (1%-8%), mechanical failure (2%-10%), hand grip failed (1%-5%), electric shock (3%) and pre-existing conditions (2%) [28, 33, 35-37, 39, 41, 43, 44]. Climber fatigue can also cause ladder falls. Specifically, 50% of occupational ladder falls were found to occur among workers that did not receive a break prior to injury, and a higher duration of total break time was associated with a later time to injury within the work shift [45]. Furthermore, studies have attributed additional factors that contribute to ladder falls (e.g. footwear, carrying equipment, lack of safety training, employee experience, insufficient ladder for the job) [28, 33, 36-38, 41, 43, 44]. Particularly, 10% to 75% of ladder fall victims reported minor or no ladder safety training [33, 36, 41]. Footwear is a known contributor to slip risk for same level falls [18, 19, 49] and is expected to also contribute to climber slip risk during ladder use. Furthermore, ladder injuries to sailors in the US Navy increased 3 times after switching to a different work boot [50].

2.2.4 Injuries

A head injury accounts for the majority of major trauma (55%) [31] and fatality (63%) [40] ladder fall cases. The most common non-fatal ladder fall injury is a fracture (28%-39%) [28, 30, 32, 34, 37, 41, 43, 46]. Ladder fall fractures are severe, incurring more medical costs and disabling days than other non-fatal ladder-related injuries [39]. In addition, fractures cases [32] and costs [39] increase with age. Non-fatal ladder falls may also result in sprains/strains (13%-39%), lacerations/avulsions (7%-11%), head injuries (1%-6%), dislocations (2%), superficial injuries (8%-41%) and other injuries (4%-9%) [28, 30, 32, 34, 37, 41, 43, 46]. Furthermore, many ladder falls result in multiple injuries (7%-35%) [28, 32, 41, 42]. The most common body parts injured from a ladder fall are the upper (21%-46%) and lower (24%-46%) extremities [28, 32-35, 37, 39, 41-43, 46]. Injuries to the trunk (8%-24%) and head (1%-17%) are also common [28, 32-35, 37, 39, 41-43, 46].

Ladder fall victims admitted to the emergency department typically arrive by ambulance (69%) [36]. Ladder fall patients are usually treated and released (i.e. outpatient) (22%-89%) [32, 34, 36, 42], but some injuries can require hospitalization (i.e. inpatient) (9%-35%) with a median time of stay reported between 5 and 8 days [32, 34-36, 41, 42]. Ladder falls injuries typically result in days away from work (51%-68%) with the mean and median days away from work reported between 21 to 57 days and 8 to 20 days, respectively [28, 30, 35, 41-43]. More than half of ladder fall victims report disabling effects [30, 39] with 30% to 39% of victims reporting continued disability after a year [31, 35]. Thus, ladder fall injuries are severe with adverse outcomes to employers and ladder fall victims.

Table 2.2.1: Epidemiology summary of ladder falls. Data source, inclusion criteria, collected data, gender, age, ladder type, action during fall and cause of fall by study. The |mean|, {median} and/or [range] of age is reported for each study when available. Studies encompass ladder-related cases in the domestic setting (shaded yellow), occupational setting (shaded blue), and the domestic and occupational (shaded gray).

Study	Data Source	Inclusion	Collected data	Gender	Age (years)	Ladder Type	Action during fall	Cause of fall
Faergemann and Larsen 2001	Hospital records and questionnaire/interview	Patients aged 15+ years admitted to the trauma section at the Odense University Hospital in 1998 after a non-occupational ladder fall	131 ladder falls	85% M 18% F	|53| [16-91]		62% standing/working 18% ascent 19% descent	53% ladder tipped or slipped 28% climber slip/misstep 12% climber lost balance 7% mechanical failure
Faergemann and Larsen 2000	Hospital records	Patients aged 15+ years admitted to the trauma section at the Odense University Hospital after a non-occupational ladder or scaffold fall injury	1462 falls • 96% ladder • 4% scaffold	72% M 28% F	|50| [15-93]			
Ackland et al. 2015	Hospital records	Adults admitted to a level 1 trauma service for ladder fall-related injuries	58 major trauma cases that were admitted to ICU after a ladder fall > 1 meter	93% M 7% F	{62} [21-89]			
Bjornstig and Johnsson 1992	Hospital records and interviews	Injured while using a ladder	114 ladder-related cases	81% M 19% F	|42| [2-77]	20% stepladder 73% straight 7% fixed ladder		19% ladder tipped 25% climber slip/misstep 4% external force or object interference 5% unstable surface 6% mechanical failure
Cabilan et al. 2017	Hospital records and questionnaires	Adult patients admitted to the emergency department for a ladder-related injury	177 ladder-related cases	82% M 18% F	|58| [18-87]	46% stepladders 30% straight 4% fixed 20% other	47% standing/working	40% ladder tipped or slipped 24% climber slip/misstep 5% climber lost balance 7% external force or object interference 7% mechanical failure 2% pre-existing condition
D'Souza et al. 2007	National Electronic Injury Surveillance System (NEISS) and NEISS weights to produce national estimates*	Nonfatal ladder-related injuries treated in US emergency departments	2,177,888 estimated ladder-related cases • |136,118| annually	77% M 24% F	|45.6|{44.0} [0.08 - 101]			
Muir and Kanwar 1993	Hospital records	Patients admitted to the wards or referred to the fracture clinic as a result of a fall from a ladder	66 ladder falls		|53| [4-92]	33% stepladders 67% non-stepladders		71% ladder tipped or slipped 29% climber slip/misstep or lost balance
Axelsson and Carter 1995	Standardized interviews from accident reports	Portable ladder accidents in the construction industry	85 portable ladder-related cases			43% stepladder 46% straight 1% fixed 11% other	66% standing/working 14% ascent 20% descent	19% ladder tipped 27% ladder slipped 8% climber slip/misstep 1% climber lost balance 4% overreaching 9% transitioning 6% external force or object interference 2% improper setup/use 5% unstable surface 2% mechanical failure 2% hand grip failed 2% pre-existing condition
Cohen and Lin 1991	National Electronic Injury Surveillance System (NEISS) and interviews	A slip, trip, misstep or fall from a portable ladder while working on a job, resulting in admission to a hospital	123 portable ladder fall-related cases			57% stepladders 39% straight 4% other	60% standing/working 14% ascent 26% descent	14% climber slip 10% climber misstep 19% overreaching 6% transitioning 15% external force or object interference 13% improper setup/use 9% mechanical failure

Table 2.2.1 (continued)

Study	Data Source	Inclusion	Collected data	Gender	Age (years)	Ladder Type	Action during fall	Cause of fall
Hakkinen et al. 1988†	Finnish National Board of Labour Protection investigation	Ladder accidents resulting in permanent disability	117 ladder-related cases			10% stepladder 70% straight 13% fixed	40% standing/working 34% ascent 24% descent	11% ladder tipped 38% ladder slipped 23% climber misstep or lost balance 10% mechanical failure 5% hand grip failed
Lombardi et al. 2011	National Electronic Injury Surveillance System (NEISS) and interviews	Workers treated in one of 65 US emergency departments after a work-related fall from a ladder	306 ladder-fall injury cases	86% M 14% F	|38.8|	51% stepladder 40% straight 9% other	51% standing/working 11% ascent 28% descent	39% ladder tipped or slipped 20% climber slip/misstep 17% climber lost balance 4% external force or object interference 1% unstable surface 4% mechanical failure 1% hand grip failed
MSHA falls from ladders 2014	Publicly available MSHA data on ladder falls	Ladder falls reports in mining	41 ladder falls	95% M 5% F	|47.9| [23 - 68]		46% standing/working 12% ascent 27% descent	19% ladder tipped or slipped 15% climber slip 4% climber misstep 19% climber lost balance 4% overreaching 13% transitioning 10% external force or object interference 6% improper setup/use
Shepherd et al. 2006	Occupational Safety and Health Administration (OSHA) reports	OSHA reports on portable ladder fatalities	277 portable ladder fatalities			6% stepladder 89% straight 1% fixed		4% ladder tipped 19% ladder slipped 19% climber slip/misstep or lost balance 22% transitioning 2% external force or object interference 4% improper setup/use 8% unstable surface 6% mechanical failure 3% electric shock 2% pre-existing condition
Smith et al. 2006	Worker's compensation claims	Ladder-related injuries	612 fracture cases • 88% fall-fracture cases	82% M 18% F	[16-79]			23% ladder tipped or slipped 25% climber slip or lost balance 7% transitioning 3% external force or object inference
Socias et al. 2014	Census of Fatal Occupational Injuries (CFOI)	Fatalities	113 ladder fall fatalities					
	Survey of Occupational Injuries and Illnesses (SOII)	Nonfatal injuries reported by employers	15,460 nonfatal ladder fall injuries	81% M 19% F				
	National Electronic Injury Surveillance System (NEISS)	Nonfatal injuries treated in EDs	34,000 nonfatal ladder fall injuries	89% M 11% F				
Vira et al. 1979	Occupational Safety and Health Administration (OSHA) fatality investigation reports	Ladder-related fatalities	116 ladder-related fatalities • 96% ladder-fall fatalities			11% stepladder 34% straight 25% fixed 24% other	32% standing/working 19% ascent 24% descent	

†Percentages estimated from chart.

2.3 Ladder Experiments

2.3.1 Ladder setup and use

Epidemiology records defines improper ladder setup/use as a ladder fall cause [28, 30, 43, 44], but improper ladder setup/use may also contribute to other ladder fall causes (e.g. ladder tipping/slipping or climber slip/misstep/lost balance) [28, 33, 36, 41]. Thus, improper ladder setup/use may contribute to more ladder falls than those reported. In one study, 90% of ladder fall victims were aware of ladder safety procedures, while only 33% followed these procedures [33]. Furthermore, 12% of ladder fall victims in another study could identify factors that would have avoided their fall [36].

Ladder setup and use research has primarily focused on the proper setup angle for a straight ladder [37, 51-56]. This research was likely motivated by ladder tipping (13%-15%) and slipping (41%-56%) leading to the majority of straight ladder falls [30, 35]. There is an optimal angle to setup a straight ladder to prevent the ladder from falling. If the ladder is setup at too steep of an angle, the ladder is at risk of tipping and if the ladder is setup at too shallow of an angle, the ladder base is at risk of slipping [37]. Chang et al. (2004, 2005) found an angle of 75° (from the horizontal) to be optimal for straight ladder setup to avoid the ladder base from slipping during ascending and descending climbs. Reducing the ladder angle to 65° was found to increase the frictional requirements of the ladder by 73% to 77% [51, 52]. Other factors that were found to increase the slipping risk of the ladder were faster climbing speeds, higher climbing heights and oily surfaces [51-53]. While setup instructions are effective in improving ladder setup position [56], ladder users still fail to setup the ladder at the correct angle [37, 55]. The average setup angle of trained professional (67.3°) was found to be well below the recommended (75°) [55]. There are multiple methods to assist in properly setting up a ladder, but the method that results in the least amount of estimated fails (i.e. the ladder base slipping) is setting up the ladder with a level (1.1% of setups resulted in an estimated fail) [54]. Other methods have a failure rate of 3.3% to 18.8% [54].

To reduce falls from improper ladder setup/use, there is a need to increase instruction and encourage safe practices. Thus, one study created an assessment tool to quantify best practices of portable ladder use in the construction industry [57]. Furthermore, ladder setup/use can be improved by improving visual indicators that assist in ladder setup; easing the use of ladder safety accessories to encourage safe practices; and improving graphical guides for safe ladder use, maintenance and flaw detection [58].

2.3.2 Standing tasks on ladders

The majority of standing tasks on ladders have been assessed from stepladders [59-63], with one study assessing a standing ladder task from a fixed ladder [64].

2.3.2.1 Reaching

Overreaching has been reported as a cause of ladder falls (4%-19%) [28, 30, 43], but has also been shown to occur in 85% of ladder falls that occur during standing or working [41]. While ladder users are recommended to keep their center line (e.g. belly button) inside the ladder rails, user have been reported to reach their center's outside of the ladder rails when reaching laterally [61, 63]. When novice ladder users initially reached laterally on a 12 ft. stepladder, their center line (i.e. belly button) remained within the ladder rails (6 mm inside ladder rails) [63]. However, when provided with additional motivation to reach farther (similar to motivation to complete a task on a ladder), they reached farther and there center line extended 84 mm outside the ladder rails [63]. When completing the same task on a 6 ft. ladder, their center line crossed the ladder rails during the initial (48 mm outside ladder rails) and motivated (115 mm outside ladder rails) conditions [63]. Furthermore, after 15 minutes of ladder acclimation, participants were found to increase their lateral reach distance by 35 mm and their traveled center line distance by 19 mm [61]. Therefore, the user's comfort with the ladder and motivation to complete the task at hand are factors that need to be considered when assessing ladder falls from overreaching.

Hand forces during lateral reaching on fixed ladders is influence by hand placement and ladder angle [64]. This study found the peak resultant hand forces to be between 27% and 34% of body weight during lateral reaches. Hand placement on the ladder rails resulted in higher hand forces than hand placement on the ladder rungs [64]. More force was utilized to pull the ladder user towards the ladder during a 90° (vertical) ladder angle, than an 80° ladder angle, resulting in higher hand forces for the vertical ladder condition [64]. If the ladder reaching force exceeds the grasping capability between the hand and handhold or exceeds the required friction to resist lateral load on the feet (e.g. in slippery conditions) [64], the climber's hand or foot may slip and cause a ladder fall. This may be indicative of some fall cases where the hand grip failed (1%-5%) [30, 37] and the climber slipped (14%-15%) [28, 43].

2.3.2.2 Tipping risk

Tipping caused 28% to 48% of stepladder falls [30, 35]. Stepladders are at risk of tipping when a ladder foot is lifted off the ground [59, 60], or the frame experiences twisting [62]. One study deemed ladder safety standards to be inadequate for testing against stepladder twisting [60], and another study aimed to improve safety tests by creating a set of minimal stability criteria for stepladders [60]. Factors that are important to stepladder stability are step height of the stepladder, medial-lateral foot placement of the climber, and medial-lateral ground angle (i.e. uneven surface) [59]. This study modeled the range of lateral weight transfer prior to stepladder foot lift-off using an inverted pendulum model. Ladder stability was 3 times more sensitive to step height than foot placement [59]. However, a step height of 40% body height, foot placement at $1/8^{th}$ the tread width to the ipsilateral ladder rail, and 3.5° ground inclination angle yielded a similar range of feasible movement prior to foot lift-off [59]. This study also recommended lateral hand-tool forces to be limited to 8% body weight to avoid stepladder movement. Thus, excessive force (6% to 7% of fall cases) [35, 43] is a likely contributor to ladder tipping cases.

2.3.3 Climbing ladders

The majority of ladder climbing literature has focused on ladders that resemble a straight or fixed ladder design. Thus, the literature below mainly represents climbing on fixed or straight ladder design, excluding one study that assessed climbing on a stepladder [65].

2.3.3.1 Expenditure

Ladder climbing can require greater oxygen uptake than other aerobic activities like uphill walking and cycling [66]. Climbing at faster rates, with additional weight, vertical ladders (90° from horizontal) and climbing without a climb assist requires more energy than slower rates, no additional weight, inclined ladders (75° from horizontal) or with a climb assist [67-71]. In these studies, participants ascended and descended a 30 m ladder [68], continuously ascended and descended a 6 m ladder for approximately 5 minutes [67], or climbed on a laddermill for 3-5 minutes [66, 69-71] for each trial. Greater oxygen consumption, heart rate and rate of perceived exertion were observed for faster, weighted, vertical and non-assisted ladder climbs [67-71]. In addition, greater forearm force exertion was observed when climbing a vertical ladder when compared to an inclined ladder [67]. Greater whole-body fatigue and localized muscle fatigue during long climbs can increase a climber's slip and fall risk [67, 72]. Thus, climber fatigue may attribute to a climber slip, misstep or lost balance.

2.3.3.2 Temporal

Ladder climbing at a 70° angle from the horizontal takes less time to climb than other ladder angles (i.e. 50°, 60°, 80°, 90°) [73]. During ladder climbing, the upper and lower limbs are in contact with the ladder longer than they are airborne, and the hands have longer contact times with the ladder than the feet [74].

Literature has described two different temporal and coordination climbing patterns [73-75]. The temporal patterns are 2-beat (upper and lower limb move in unison) and 4-beat (movement of each limb is staggered). The two coordination patterns are lateral (ipsilateral limbs move together) and diagonal (contralateral limbs move together). Conflicting information exists between the most common ladder climbing pattern [73-75]. Furthermore, the majority of climbers switch between patterns [74]. Thus, there does not appear to be a clear preferred climbing pattern among climbers. One study found the diagonal pattern to be more natural [75], and another study suggested 2-beat, lateral climbing to enhance stability [73]. However, Pliner and Beschorner (2017) did not find climbing patterns to influence a climber's ability to recover after a ladder climbing perturbation (Appendix A.2).

2.3.3.3 Kinetics

Climbing kinetics reveal the primary role of the hands and feet are to stabilize and support the body during ladder climbing, respectively [76-78]. Resultant hand forces utilized during climbing have been reported between 10% to 42% of the climber's body weight [72, 76]. Peak resultant hand force is greater for rung than rail hand placement [76]. However, the medial-lateral hand force component is greater for the rail than rung hand placement. These authors suggest higher medial-lateral forces to destabilize the climber from the center of the ladder [76], but these effects have not been confirmed. Hand forces tend to decrease with a greater ladder inclination angle (i.e. the ladder is farther from vertical) [72, 76], and this effect is more pronounced for rail than rung hand placement [76]. Thus, the stabilizing role of the hands have been attributed to be more important at steeper ladder angles (i.e. the ladder is closer to vertical) [75]. Resultant foot forces utilized during climbing have been reported between 55% to 105% of the climber's body weight, with higher values at greater ladder inclinations [72, 76]. Ladder climbing kinetics has also been studied for below the knee amputees [65]. This study found below the knee amputees to climb asymmetrical, compensating with the hand ipsilateral to the prosthetic limb.

Loading conditions are affected by climbing speed and rung spacing. Faster climbing speeds are associated with greater hand and foot forces [65, 77, 79]. A greater rung spacing (i.e. 40.6 cm and 45.7 cm compared to 30.5 cm) results in a more variable distribution of forces loaded onto the ladder [79]. This irregular climbing kinetics can increase the likelihood of a climbing misstep [79]. Climbing forces exceed body weight, so ladder designs that can uphold loads of body weight (of the respective population) multiped by 1.7 in the vertical and 0.4 in the anterior-posterior directions have been recommended [79]. Thus, loading conditions have been used to guide ladder safety standards [79].

2.3.3.4 Kinematics

The climber's body position varies with ladder inclination. Body angle with respect to the vertical (an estimate of the center of mass) has been reported between 14° and 38° across vertical and inclined ladders [80, 81]. On vertical ladders, a minimum distance of 30.5 cm is required between the climber's waist and the ladder to enable normal climbing [79]. This required waist-to-ladder distance increases at a greater ladder inclination (i.e. an individual climbs with their waist farther from the ladder) [79]. Yet, the climber's center of mass is closer to the ladder at greater ladder angles than steeper ladder angles [78, 81]. To facilitate both of these, the climber adopts a more crouched posture (i.e. knees bent, hips out) when climbing inclined ladders, aiming to maintain their center of mass over the supporting foot while minimizing stresses on the arms [75, 79].

Dewar (1997) describes additional detail on body movements (i.e. pelvis and trunk displacement and rotation, and rotations of the knee and hip joints) during ladder climbing and how they compare to gait [75]. Notably, large differences in movement patterns have been observed for taller and shorter adults and may be attributed to a fixed ladder design (e.g. rung spacing) that is set to the average adult dimensions [75]. This greater variability can increase an individual's probability of experiencing a climbing error (e.g. misstep) [75].

The foot position is also affected by ladder angle. The foot angle with respect to the horizontal and has been reported to be between -2° and 27° during ladder climbing [80, 81]. The anterior position of the foot with respect to the ladder rung mid-point has also been investigated and found to be between 16% and 36% of foot length during ladder climbing [80, 81]. A greater foot angle during ladder climbing appears to be associated with steeper ladder angles, but the change in the anterior foot placement across ladder angles is less pronounced [81].

2.3.4 Ladder handholds

The hands are a critical component of ladder fall recovery [82]. Thus, multiple studies have simulated a ladder falling environment of the upper body to investigate the biomechanical relationship between the hand and ladder handhold (i.e. rungs or rails) [83-88]. To simulate a ladder falling event of the upper body, participants were secured (seated or standing) and asked to hold onto a ladder handhold until the handhold broke free from their grasp while the participant was lowered or the rung was raised [84-88]. The peak force generated onto the rung prior to hand-handhold breakaway was recorded to assess upper body strength. These tests are referred to as breakaway strength tests. Another study estimated the ladder fall hand-handhold relationship by recording grip strength and reaction time using a dynamometer and sliding rail apparatus [83].

Overall, these studies found increased friction and grasping a ladder rung to be more beneficial for arresting a ladder fall than low friction and grasping a ladder handrail [83-88]. Across different conditions (friction, handhold design) breakaway strength values were reported to be between 50% and 117% body weight [84, 87, 88]. Breakaway force values were higher for horizontally orientated handholds (e.g. rung) and handholds that enable increased friction (high friction gloves, fixed rung) compared to a vertically orientated handhold (e.g. rail) and low friction handholds (e.g. low friction gloves, frictionless rung) [84, 85, 87, 88]. In addition, participants generate more force with a circular than rectangular cross-sectional handhold [85, 87]. Some participant were unable to support half their body weight with a rectangular rung [85], indicating an increased ladder fall risk if foot placement was lost. However, climbing perturbation or prospective ladder fall research is needed to confirm these relationships with ladder fall recovery.

Other findings from these studies were as followed. Low friction gloves increased muscle effort and distance to arrest a vertically rising rung compared to high friction gloves [86]. A higher hand position (e.g. hand above head) increased downward pull force generated onto a rung compare to a lower hand position (e.g. hand at shoulder level) [84]. Males generated higher hand-handhold forces than females [84, 87, 88]. Thus, modifying components of the hand and handhold interaction may assist in preventing ladder falls.

2.3.5 Climber fall risk

While many researchers attribute greater variability in temporal, kinetic and kinematic climbing variables to increase an individual's potential for experiencing a climbing error (e.g. slip or misstep) [75, 77, 79], ladder perturbation or prospective ladder fall research is needed to confirm this. Prior to content in this dissertation, only two publications (one by the author of this dissertation) from one ladder climbing study, facilitated a ladder experiment with a climbing perturbation [80, 82]. This study did find more variable kinematics to be associated with a greater slip risk. Specifically, participants that climbed with a more variable body and foot angle experienced a ladder climbing slip [80]. In addition, a greater foot angle (toe up with respect to the horizontal) was associated with a slip outcome. This study also found individual and environmental factors to play a role in slip risk. That is, a ladder climbing slip was 6 times more likely when foot placement was restricted, and age group was a predictor of slip risk, with younger adults (18-24 year old) slipping the most, followed by the eldest age group (45-64 year old) [80]. Furthermore, muscle onset times to a climbing slip were slower when participants climbed with rails as opposed to the rungs [82]. This suggests that climbing with the rungs may assist the climber in activating a faster recovery response to arrest their fall.

The required coefficient of friction (RCOF) for ladder climbing is a potential estimate of climber slip risk. A greater RCOF is expected to be associated with a greater slip risk, as RCOF has been shown to predict same level slips [16]. The relationship between RCOF and foot angle during ladder climbing also agrees with the biomechanics of participants that experience a foot slip [80, 81]. Specifically, a greater RCOF is associated with a greater foot angle [81] and a greater foot angle has been found to be associated with climber's that experienced a foot slip [80]. A steeper ladder angle (90° compared to 82.8° and 75.5°) was also found to increase the RCOF [81], suggesting slip risk to be greater when climbing vertical ladders.

Footwear is a critical factor to consider when assessing climber slip risk. Inappropriate footwear was found to contribute to 27% of ladder-related injuries [36] and may have contributed to the tripling increase in US Navy ladder mishaps [50]. Furthermore, footwear's effect on climbing mechanics shows potential to reduce ladder slip risk. During ladder climbing, maximum dorsiflexion corresponds to timing of greatest exerted force onto the ladder rungs, resulting in the highest potential for a foot slip [89]. Compared to climbing barefoot, shoes reduce the required dorsiflexion in the foot, but not the climber's ability to exert force [89]. Therefore, proper footwear can lower foot angle during ladder climbing to reduce slip risk.

2.4 Gaps in the Literature

There are many pathways to a ladder fall (Figure 2.4.1). This is due to the possibility of different ladders (stepladder, straight, fixed), ladder actions (standing/working, ascending/descending), and causes leading to a fall (ladder tipping, ladder slipping, climber slip, climber misstep and lost balance). Furthermore, some of these causes may be linked to other ladder fall risk factors (e.g. overreaching leading to lost balance or ladder tipping). There are some pathways to ladder falls that have been explored (e.g. straight ladder slipping during climber ascent and descent), pathways that need additional research to be confirmed (e.g. influence of high friction glove on ladder fall recovery), and many pathways that are unexplored (e.g. falls due to lost balance and climber missteps). Ladder perturbation or prospective ladder fall research is needed to confirm some of these pathways, and additional research on safe and effective ladder use is needed to understand individual, environmental and the interfacing factors between the individual and environment that contribute to ladder fall risk.

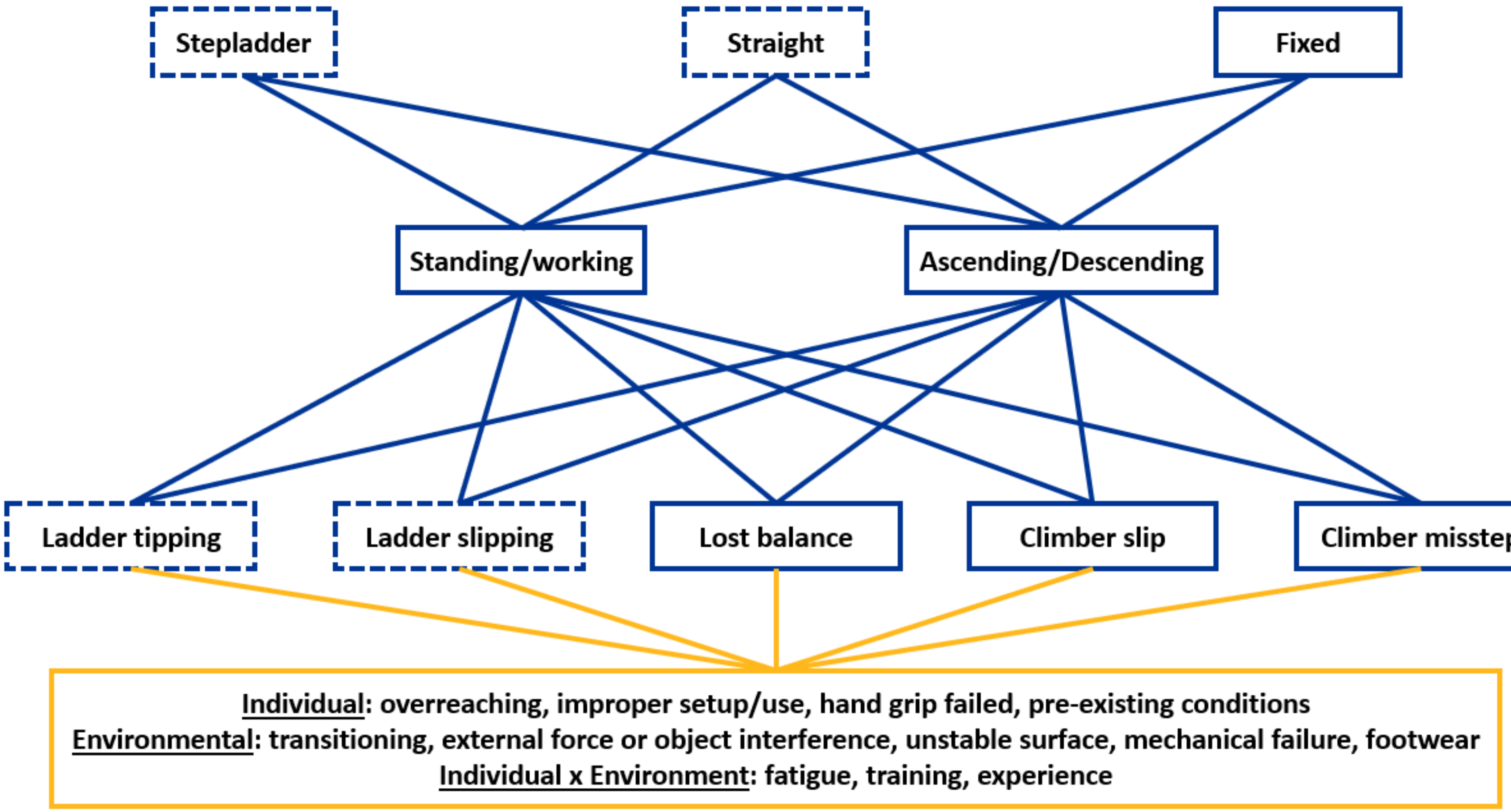


Figure 2.4.1: Pathways to a ladder fall. A ladder fall can occur while the user is standing/working on or climbing (ascending/descending) a stepladder, straight or fixed ladder. General causes leading to a ladder fall are the ladder tipping or slipping and a climber slip, misstep or lost balance. Ladder tipping or slipping is possible from portable stepladders and straight ladders (dashed boxes), but not fixed ladders. Additional factors can attribute to general ladder fall causes and can be individual, enviromental, or individual and enviromental based (factors inside yellow box).

This dissertation will fill gaps in the literature by exploring new ladder fall pathways and supporting some previously-considered ladder fall pathways. Specifically, this dissertation will 1) determine individual factors that influence task performance on a stepladder and 2) determine individual, environmental and biomechanical factors of ladder fall severity after a climbing perturbation. Additional background and motivation by study is provided in Chapters 3.0 and 4.0.

2.5 Safety Needs Diversity

Knowledge gaps in ladder fall research may be attributed to the lack of diversity in engineering, particularly in the safety field. While women and minorities make up 50% and 38% of the US population, respectively, only 20% of engineering bachelors are earned by women and minorities (Figure 2.5.1) [90].

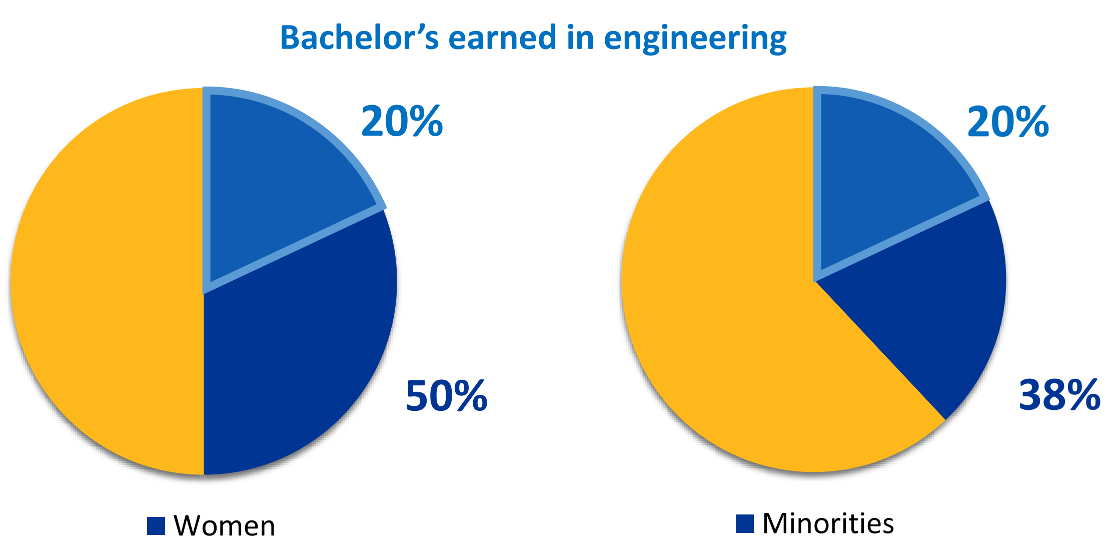


Figure 2.5.1: Percent of bachelor's earned in engineering by women and minorities. Women and minorities make up 50% and 38% (dark blue) of the US population. Only 20% of bachelor's in engineering are earned by women and minorities (light blue) [90].

This poor representation of women and minorities has a negative impact on the applicability of research to different populations and can be reflected in research gaps. This may explain why the majority of ladder experiment studies only used male participants [37, 55, 61, 63, 65, 69, 71, 72, 74, 75, 77, 78, 89, 91] or did not differentiate by gender [60, 67, 79]. In addition, only three ladder epidemiology studies collected information on race/ethnicity [34, 42, 46], and only two focused on domestic-based ladder falls [32, 41]. This has a negative effect on female, minority and domestic ladder users that are not being represented in these studies. For example, the Occupational Safety and Health Association (OSHA) standards for maximum ladder rung spacing (12 inches between rung centers) are based-off climbing kinetics, but the authors of this study did not separate or specify gender and race/ethnicity [79, 92]. Rung spacing larger than 12 inches resulted in more variable climbing kinetics, increasing ladder climbing misstep risk [79]. Similarly, ladder climbing kinematics is more variable for persons of shorter stature [75], increasing their risk of a ladder climbing slip [80]. On average, US females are 12.7 cm shorter than males and white males are taller than black (2.5 cm shorter), Asian (7.6 cm shorter) and Hispanic (7.6 cm shorter) males [93]. While the maximum rung spacing standard may be sufficient for the average white male climber, the standard is likely insufficient for the average female climber and climbers from other race/ethnic groups. This may be one of the factors contributing to Hispanics incurring higher rates (nearly double) of fatal and non-fatal ladder fall injuries compared to white, non-Hispanics [42]. This supports the need to increase diversity in the STEM fields like safety.

2.6 The Biomechanics Bridge to STEM

Combining Science, Technology, Engineering and Mathematics (STEM) topics with non-STEM topics can engage students with diverse interests. Previous work has successfully engaged students with robotics by relating concepts to arts and storytelling [94]. However, interests are personal and all students might not relate to the arts or storytelling. Relating engineering concepts to students' specific-interests may be a useful pedagogy to improve engagement of underrepresented persons in the STEM fields.

The field of biomechanics is unique because it bridges several fields. The American Society of Biomechanics (ASB) defines five specialties within biomechanics: biological science, exercise and sports science, health science, ergonomics and human factors, and engineering and applied science. Furthermore, biomechanics has been defined as a bridge between student interests and underrepresented students pursuing STEM [95]. This is because biomechanics is intertwined with many of the technological advances that interest students: sports performance, video game graphics, animation, virtual environment systems, smart phone facial recognition. Furthermore, biomechanics can engage students through career interests. Whether the career interests are occupations within the five specialties of biomechanics or through the safety applications of biomechanics. That is, the ergonomics and human factors side of biomechanics can be applied to any career to engage student interest. Therefore, biomechanics can be used to link students' specific interests to STEM.

This dissertation aims to improve diversity in the STEM fields by investigating the relationship between student-specific content and engagement in biomechanics. Additional background and motivation for this study is provided in Chapter 5.0.

3.0 Characterizing User-specific Factors of Ladder Fall Risk

This chapter investigates the influence of individual (vision, proprioception and sensation, upper arm dexterity/coordination and stability, strength, balance, cognition, psychological) factors on ladder task performance. In addition, differences in ladder task performance is investigated between younger and older adults under different cognitive demands. The discussion of this study is divided into two sections, Section 3.1.5.1 Part 1: Individual measures on ladder task performance and Section 3.1.5.2 Part 2: Ladder use by age group. This chapter is in preparation to be submitted for publication. Preliminary results for this chapter have been published through conference abstracts [96-98]. Additional study methodology (Appendix B.1) and supplementary analyses (Appendix B.2) can be found in Appendix B.

3.1 Individual Factors that Influence Task Performance on a Stepladder

3.1.1 Abstract

Ladder falls are a common cause of injury in the domestic setting, particularly among older adults. There is a need to understand contributing factors of safe and effective ladder use and how ladder use differs between age groups. This study investigated the influence of individual factors on ladder task performance. Older and younger adults climbed a household stepladder to change a light bulb under single and cognitive dual task conditions. Ladder task performance was quantified from a summative measure of task completion time and standing stability. Individual measures (vision, proprioception and sensation, upper arm dexterity/coordination and stability, strength, balance, cognition, psychology) were assessed in the older adults. Balance, cognition, upper arm dexterity and coordination, edge contrast sensitivity, knee strength and age were found to be predictors of ladder task performance in older adults. The older adults were found to prioritize balance and the younger adults were found to prioritize the secondary task. This knowledge can help guide ladder fall interventions, such as, screening for individuals at greater ladder fall risk and age-specific safety instructions.

3.1.2 Introduction

Falls are the leading cause of disabling injury in the workplace [1] and account for an estimated $175 billion in US fatal and non-fatal injury costs [4, 5]. The majority of occupational fatal falls are from a height [24] with most of these injuries occurring from a ladder [25]. In addition, epidemiological records report ladder fall incidents in the domestic setting to be at least as prevalent as in the workplace [31-34]. Research on occupational ladder use has assisted in improving ladder setup and design [52, 58, 79, 80], but there has been little investigation on ladder use in the domestic setting. Furthermore, ladder fall incidence rates are highest among older adults (i.e. retirement age or older) [32]. The majority of ladder fall incidents occur among men [31, 32], but women are also susceptible to experiencing a ladder fall, particularly while using a stepladder indoors [41]. To our knowledge, no study has investigated ladder use among older adults. Thus, there is a need to investigate factors associated with ladder falls in the domestic setting among older men and women.

Ladder falls commonly occur while the user is working from the ladder [30, 41, 43], but only a few studies have investigated ladder fall risk while completing a task on a ladder [59-61]. While these studies assessed stability of the ladder or ladder user, they did not assess performance in the secondary task. Poor performance in completing a secondary task on a ladder can increase ladder use exposure (e.g. increased time and ladder climbing attempts to complete the task) and may also be relevant to a ladder fall risk. Thus, there is a need to consider stability and task completion performance when assessing ladder fall risk of a user working from a ladder.

A person's task performance (e.g. stability and task time) to complete a task on a ladder may be influenced by individual factors. Physiological factors (strength, reaction time, standing balance) are known predictors of coordinated stability (controlled leaning balance) and maximum lean distance measured at the waist [99]. Furthermore, standing stability measures (e.g. center of pressure sway range, frequency and area) are influenced by elevation [100] and the presence of a secondary task [101]. In these studies, psychological factors (anxiety and perceived threat) were found to have an effect on stability measures and secondary task performance [100, 101]. Reduced performance in secondary task completion among older adults is believed to be attributed to a limited capacity in cognitive resources. Older adults are known to prioritize standing stability in conditions of increased postural threat [101], but the standing stability of older adults can worsen with higher cognitive demands [102]. Completing a secondary task on a ladder requires individuals to stand at an elevated level, utilizing cognitive resources for standing stability and secondary task completion. Therefore, physical and cognitive abilities and the psychological outlook of the individual are likely to influence task performance on a ladder.

The purpose of this study is to determine individual factors (physiological, cognitive psychological) that influence task performance (stability and task completion metric) on ladder use among older adults. Individual physiological and cognitive abilities and psychological outlook were assessed from clinical assessments. Task performance was assessed using a domestic-based ladder task. Specifically, participants were asked to change a light bulb on a household stepladder under two cognitive demands (single task, cognitive dual task). In addition, differences between older and younger adults in task performance were examined while completing the task under two levels of cognitive demand. Below are our registered hypotheses (https://osf.io/xv2ab/):

Hypothesis 3.1.1: Individual factors will influence task performance of changing a light bulb on a household stepladder.

Hypothesis 3.1.2: A greater difference in standing stability and task completion time between cognitive demands will be observed in older adults than younger adults.

Findings from this work will impact future ladder fall interventions. Specifically, knowledge of individual factors that influence task performance on ladder use can lead to screening methods for identifying individuals at risk of experiencing a ladder fall and facilitate ladder redesign to mitigate physical and cognitive abilities and psychological outlooks associated with reduced task performance.

3.1.3 Methods

3.1.3.1 Participants

For this study, 104 older adults (52 female, aged: 72.9 ± 5.5 yrs., height: 1.7 ± 0.1 m, weight: 72.5 ± 13.8 kg) and 20 younger adults (10 female, aged: 27.3 ± 5.2 yrs., height: 1.7 ± 0.1 m, weight: 66.3 ± 13.4 kg) participated. Participants were recruited through advertisements, community presentations, volunteer call registries and word-of-mouth. Participants were recruited and assessed from March 2018 to August 2018. Participants were eligible if they were between the ages of 18 and 40 years old (younger adults) or older than 65 years old (older adults). Additional inclusion criteria consisted of living independently at home in the community or retirement village and willing to change a light bulb while standing on the second step of a household stepladder. Exclusion criteria consisted of use of a mobility aid inside the home, a neurological disorder (e.g. Parkinson's disease, multiple sclerosis, dementia/Alzheimer's), weight over 120 kg, and the inability to change a light bulb on a ladder without pain. Human research ethics approval was obtained from the University of New South Wales and all participants provided informed written consent prior to participating in the study.

Participants underwent a 2-hr laboratory visit to assess physical and cognitive capabilities, and task performance while changing a light bulb on a household stepladder. In addition, participants completed basic-health questionnaires and psychological assessments online or by mailed hard copies.

3.1.3.2 Individual measurements

Questionnaires/assessments consisted of demographics, baseline health, generalized anxiety disorder (GAD-7) [103], risk-taking [104], and ladder use surveys. The older participants completed additional questionnaires/assessments on fall history, disability (WHODAS) [105], patient health (PHQ-9) [106], late life function and disability (LLFDI) [107], and fear of falling (Icon-FES) [108].

During the laboratory visit, participants were asked to undertake physical and cognitive assessments. All participants completed upper body assessments from the Upper Limb Physiological Profile Assessment (ULPPA) (Appendix B.1.1) [109]. Specifically, participant's upper body capabilities were assessed from unilateral movement and dexterity (finger tapping, loop & wire test) [109], bimanual coordination (bimanual pole test) [109], proprioception (position sense at elbow) [109], skin sensation (tactile sensitivity) [110], arm stability (total path traveled by the outstretch arm) [109] and muscle strength (grip strength) [111] assessments. All participants were asked to complete the Trail Making Tests A and B to assess cognitive processing speed and executive function (Appendix B.1.2) [112]. Additional physical assessments for the older participants consisted of the short-form Physiological Profile Assessment (PPA) (vision contrast, reaction time, lower limb proprioception, knee strength, and sway on ground and foam) (Appendix B.1.3) [113, 114] and a coordinated stability test (Appendix B.1.4) [99]. Participants performed single limb tasks (e.g. reaction time, knee strength) with the dominant limb. An additional cognitive assessment consisted of the Mini-Mental State Examination (secondary screening for dementia) [115]. Healthy younger adults are known to score well on these assessments with minimal variation [113, 116]. Thus, the younger participants were not asked to complete these assessments.

3.1.3.3 Ladder task

Participants were asked to climb a household stepladder to change a light bulb (Figure 3.1.1). The household stepladder had three steps, a handrail and a tray. Participants only climbed to the second step of the stepladder. The use of the handrail was optional. A replacement light bulb was set on the ladder tray. The height of the fixture that held the light bulb was adjusted via a vertical linear bearing. The height of the light bulb was positioned to the participant's hand height when standing on the second ladder step with 90º shoulder and elbow flexion. Prior to climbing the stepladder, participants practiced changing the light bulb (Edison, screw-base) at ground level. Participants completed this task twice, once under two cognitive demands (dual task: while naming animals, single task: without a cognitive distraction, order randomized). Participants started on ground level behind a start line (one step away from the stepladder) and were asked to complete the task as "quickly and safely as possible". The task involved climbing to the second step of the ladder, changing the original light bulb with the replacement light bulb, setting the original light bulb onto the ladder tray, descending the ladder and stepping behind the start line. The time required to complete the task was measured using a stopwatch. The number of animals named was recorded by a research assistant and confirmed from audio recordings.

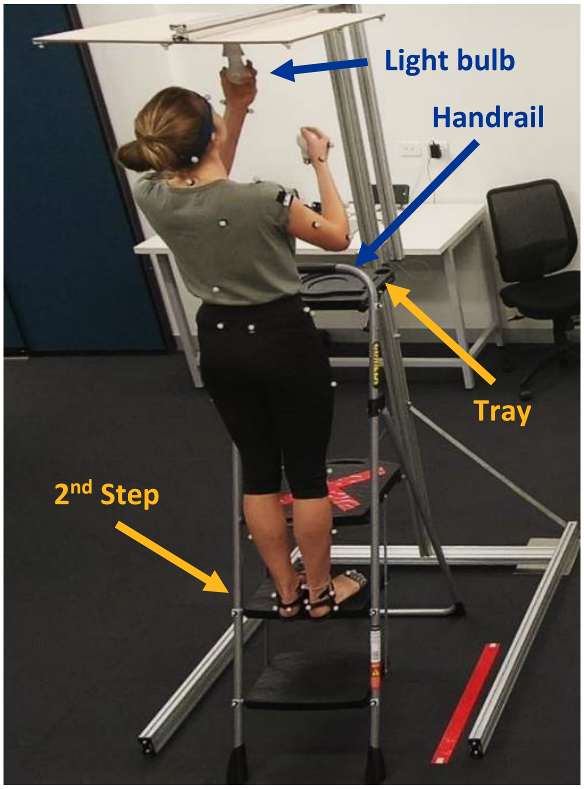


Figure 3.1.1: Ladder apparatus for light bulb experiment. Participants climbed to the second step of a household stepladder to change a light bulb. The light bulb fixture was fixed to a wood and aluminum frame that could be adjusted in height. The stepladder had a tray and a handrail. The tray was used to hold the replacement light bulb. Participants could choose to use or not use the handrail.

Participant kinematic data were collected (at 100 Hz) from reflective markers placed on the participant and experimental apparatus from an 8-camera motion capture system (Vicon Motion Systems Ltd., Oxford, UK.) (Appendix B.1.9). Participants were equipped with a custom-marker set based on the Vicon Plug-In Gait model (Appendix B.1.5, Appendix B.1.6) [117]. Specifically, the Plug-In Gait model was used with additional markers placed on the medial elbows, waist, medial knees, medial ankles, and the medial and lateral sides of the foot. The experimental apparatus was equipped with markers to determine the participant's position relative to the setup. Six markers were placed on the ladder support rails, three on each side, at heights equal to the 1st ladder step, 2nd ladder step, and on the handrail. Five markers were placed on the fixture (rectangular wood frame) that supported the light bulb: three markers were placed in a corner and two markers were placed in between the corner markers and aligned with the middle of the light bulb (Appendix B.1.7, Appendix B.1.8). Kinetic data were collected (at 200 Hz) from two force plates below the front and back ladder feet.

3.1.3.4 Data analysis

3.1.3.4.1 Individual measures

Individual measures were quantified for each assessment and based on the scoring of the corresponding clinical assessment (Table 3.1.1). Physical measures were separated into five sensorimotor domains: vision, proprioception and sensation, upper arm dexterity/coordination and stability, strength, and balance. A cognitive and psychological domain grouped the cognitive and psychological assessments, respectively. Thus, there was a total of 7 domains to categorize individual measures. Higher values in physical and cognitive assessments were typically associated with reduced performance; the exceptions being edge contrast sensitivity, finger tapping, strength measures and the mini-mental state exam, where higher values were associated with better performance. Higher values in the psychological assessments were associated with greater risk-taking, anxiety and fear of falling. To mitigate the influence of outlying scores, individual measures were capped to the mean ± 3*standard deviations.

Table 3.1.1: Scoring and performance association by individual measure. Individual measures are categorized by domain (vision, proprioception and sensation, upper arm dexterity/coordination and stability, strength, balance, cognition, psychological). Additional details on assessment procedures and scoring can be found in the listed references.

Individual Measure	Scoring	Performance association with high value	Reference
Vision			
Edge contrast sensitivity	Score from Melbourne Edge Test (MET) – identifying the direction of the line created from two contrasting semi-circles	Better contrast vision	Verbaken and Johnston 1986
Proprioception and sensation			
Lower limb proprioception	Mean error in matching the balls of the feet together	Reduced proprioception	Lord et al. 2003
Elbow proprioception	Mean error in matching the pointer finger position of the dominant hand to the pointer finger of the non-dominant hand	Reduced proprioception	Ingram et al. 2019
Tactile sensitivity	Lightest force that can be sensed on the palm of the dominant hand	Reduced sensation	Bell-Krotoski et al. 1995
Upper arm dexterity, coordination and stability			
Finger taping	Total number of taps made by the pointer finger of the dominant hand in 10 seconds	Better movement and dexterity	Ingram et al. 2019
Loop & wire	Total number of wire touches that occurred when participants attempted to move a ring through a copper wire maze as fast and accurately as possible	Reduced movement and dexterity	Ingram et al. 2019
Bimanual pole test	Time to move through a pole maze, pulling the inner and outer layers of the pole out and together	Reduced bimanual coordination	Ingram et al. 2019
Arm stability: eyes open	Total path length traveled, recorded from an IMU on the wrist when holding the outreached dominant arm as straight as possible for 30 seconds – participant eyes open	Reduced arm stability	Ingram et al. 2019
Arm stability: eyes closed with weight	Total path length traveled, recorded from an IMU on the wrist when holding the outreached dominant arm as straight as possible for 30 seconds – participant eyes closed, with 250 gram weight in hand	Reduced arm stability	Ingram et al. 2019
Strength			
Knee strength	Maximum knee extension strength	Greater strength	Lord et al. 2003
Grip strength	Maximum grip strength between two parallel bars	Greater strength	Roberts et al. 2011

Table 3.1.1 (continued)

Balance			
Sway: eyes open, on floor	Estimated total path length traveled by the pelvis when standing for 30 seconds – eyes open on floor	Reduced balance	Lord et al. 2003
Sway: eyes open, on foam	Estimated total path length traveled by the pelvis when standing for 30 seconds – eyes open on foam	Reduced balance	Lord et al. 2003
Coordinated stability	Score obtained from coordinated pelvis movement test	Reduced balance	Lord et al. 1996
Cognition			
Hand reaction time	Mean time to left click on a computer mouse in response to the illumination of a red LED	Slower reaction time	Lord et al. 2003
Trails A	Time required to trace a line between numbers randomly distributed on a page in sequential order	Reduced cognitive processing	Tombaugh 2004
Trails B	Time required to trace a line between numbers and letters randomly distributed on a page in number-letter sequential order	Reduced cognitive processing and executive functioning	Tombaugh 2004
Trails B-A	Difference in time to complete Trails A and Trails B	Reduced executive functioning	Tombaugh 2004
Mini-Mental State Exam	Score obtained for answering and completing memory tasks correctly	Better memory	Tombaugh and McIntyre 1992
Psychological			
Risk-taking	Total score on risk-taking questionnaire	Greater risk-taker	Butler et al. 2014
GAD-7	Total score on general anxiety disorder questionnaire	More anxious	Spitzer et al. 2006
Icon-FES	Total score on fear of falling questionnaire	Greater fear of falling	Delbaere et al. 2011

3.1.3.4.2 Standing stability

Standing stability was based on center of pressure (COP) measurements. The COP was quantified from summative forces and moments from the two force plates below the stepladder [118] (Equations 3.1-3.4).

$$COP_{x_i} = \frac{-h * F_{y_i} + M_{x_i}}{F_{z_i}} \tag{3.1}$$

$$COP_{y_i} = \frac{-h * F_{x_i} - M_{y_i}}{F_{z_i}} \tag{3.2}$$

COP_{x_i} and COP_{x_i} represent the COP with respect to the force plate (localized COP location), where *x (anterior-posterior)*, *y (medial-lateral)* and *z (superior-inferior)* indicate the direction of the component, *i* denotes which force plate (either 1: front force plate or 2: back force plate), *h* is the height from the force plate surface to vertical centroid of the 2nd stepladder step, *F* signifies the force and *M* signifies the moment.

$$COP_{x_{global}} = \frac{\left[F_{z_1} * \left(O_{x_1} - COP_{x_1}\right)\right] + \left[F_{z_2} * \left(O_{x_2} - COP_{x_2}\right)\right]}{F_{z_1} + F_{z_2}} \tag{3.3}$$

$$COP_{y_{global}} = \frac{\left[F_{z_1} * \left(O_{y_1} - COP_{y_1}\right)\right] + \left[F_{z_2} * \left(O_{y_2} - COP_{y_2}\right)\right]}{F_{z_1} + F_{z_2}} \tag{3.4}$$

$COP_{x_{global}}$ and $COP_{y_{global}}$ represent the COP with respect to the global coordinate system. Nomenclature is identical to the above, where *1* denotes the front force plate, *2* denotes the back force plate, and *O* signifies the origin of the force plate in the global coordinate system.

The global COP was utilized to calculate measures of standing stability. Of the measures calculated, one traditional standing stability measure was selected and one task-specific standing stability measure was created to assess stability on a stepladder. These standing measures were quantified when both feet were established on the 2nd stepladder step. To eliminate transition effects, the two seconds after the feet were established and the second prior to foot liftoff were excluded from the data analysis. For traditional standing stability measures, the time normalized path length, root-mean-square (RMS), and elliptical area (the area that the COP remains within 95% of the assessed time) were calculated [119]. COP elliptical area had the strongest relationship with a clinical score of general fall risk in older adults (Appendix B.2.1) [96, 97]. Thus, COP elliptical area was selected as the traditional standing stability measure, where a greater elliptical area is generally interpreted as reduced stability. The created standing stability measure was specific to the fall risk in the ladder task. Specifically, the minimum anterior-posterior (y-direction) distance between the COP to the posterior edge of the 2nd step (referred to as edge distance hereafter) was calculated (Figure 3.1.2). This measure is relevant to stability on a stepladder because posterior COP displacement during quiet standing is associated with backward balance loss [120], which was expected to be the most likely fall direction for this experiment. Thus, a smaller edge distance (i.e. the COP is closer to the posterior step edge) was associated with greater instability.

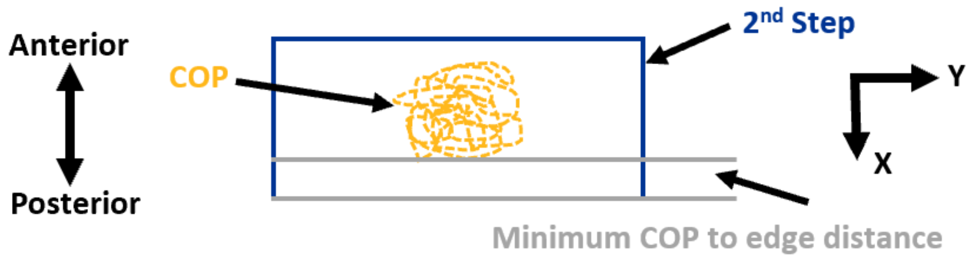


Figure 3.1.2: Top view schematic of the 2nd stepladder step. The yellow dotted line represents the calculated center of pressure (COP) with respect to the 2nd step (blue outline). Edge distance was found from the minimum distance between the COP and posterior step edge (distance between the gray lines).

Equipment malfunction of a force plate prevented COP calculation in 9 trials among 8 older adults. A combination of equipment malfunction and extreme outlier measurements occurred in 2 trials in 1 younger adult. Thus, this data was excluded from data analysis.

3.1.3.4.3 Task completion metric

The scoring for accomplishing the task (i.e. changing a light bulb on a household stepladder) was based-on time taken to complete the task. This metric was measured from when the participant crossed the start line at the beginning of the task to when the participant re-crossed the start line at the end of the task. Therefore, a longer time to complete the task indicated poorer performance in accomplishing the task.

3.1.3.4.4 Task performance

A shorter task completion time and better standing stability would contribute to safe and effective ladder use. A greater time on the task increases exposure time, potentially increasing the probability of experiencing a ladder fall. However, the standing stability of an individual may suffer if they complete the task too fast, increasing the likelihood of the individual losing balance

– leading to a ladder fall. To assess safe and effective ladder use, this study quantified task performance as a summative z-statistic from task completion time and standing stability (Equations 3.5 & 3.6). Specifically, a z-statistic was created for each traditional (elliptical area) and ladder specific (edge distance) stability measure by cognitive demand. To facilitate a normal distribution, task completion time and standing stability measures were capped to the mean ± 3*standard deviations, if necessary, prior to z-statistic calculations.

$$Task\ Performace_{traditional} = (Z_{elliptical\ area} + Z_{task\ time}) * -1 \qquad 3.5$$

$$Task\ Performace_{ladder\ specific} = Z_{edge\ distance} - Z_{task\ time} \qquad 3.6$$

The sign of task time and elliptical area were reversed so that a higher value was associated with better task performance for all metrics.

3.1.3.5 Statistical analysis

To test Hypothesis 3.1.1, a two-step hierarchical regression was performed to determine individual measures that predict task performance in older adults. The first step consisted of a stepwise regression. To minimize effects of multi-collinearity, only the measure within each domain that had the strongest correlation with task performance (vision, proprioception and sensation, upper arm dexterity/coordination and stability, strength, balance, cognition, psychological) was entered into the stepwise regression (7 predictors). Bivariate Pearson's correlations were performed between task performance and each individual measure to determine the measures with the highest correlation. If needed, square root and logarithmic transforms were performed on individual measures to ensure distributions with a skewness < 1.0. In the second step, age and gender were entered into the model as confounding factors. This process (Pearson's correlations and hierarchical regression) was performed for each cognitive demand condition (naming animals and no cognitive distraction) and for each task performance measure (traditional and ladder specific). A significance level of 0.05 was used.

To test Hypotheses 3.1.2, three ANOVAs were performed to determine the effects of cognitive demand on ladder use between older and younger adults. Two ANOVAs tested standing stability as the dependent variables (elliptical area and edge distance). The third ANOVA tested task completion time as the dependent variable. Age group (older, younger), cognitive demand (single, dual) and the interaction (age group x cognitive demand) were the predictors entered into the model. Participant number and gender were added to the model as a random and confounding variable, respectively. Participants with missing COP measurements (due to equipment malfunction of the force plate) were excluded from the ANOVAs testing standing stability as the dependent variable. Log transforms were applied to elliptical area and task completion time to obtain unimodal distributions with a skewness < 1.0. To better understand the differences in ladder use for older and younger adults, an independent *t*-test was performed between older and younger adults to investigate differences in animal naming rate (Table 3.1.2). A significance level of 0.05 was used. Statistical software (IBM SPSS, Version 24. IBM Corp., Armonk, NY) was used to perform the analyses.

Table 3.1.2: Statistical analyses. The dependent and predictor variables in each statistical analysis. Additional test details are noted (separated test, random and confounding variables). Pearson's correlations, hierarchical regression, ANOVAs and an independent *t*-test were performed to test the study hypotheses.

Analysis	Separated by	Dependent variable	Predictor variable	Other variable
Pearson's correlation	Cognitive demand	Task performance measures	Individual measures	NA
Hierarchical regression	Cognitive demand	Task performance measures	Highest correlated individual measure per domain	Gender (confounder), age (confounder)
ANOVA	NA	Standing stability measures, task completion time	Age group, cognitive demand, interaction	Participant number (random), gender (cofounder)
Independent *t*-test	NA	Animal naming rate	Age group	NA

3.1.4 Results

The mean (standard deviation) task completion time for older adults was 24.3 (7.6) seconds and 27.2 (8.5) seconds for the single and dual task conditions, respectively. The mean (standard deviation) elliptical area and edge distance for older adults in the single task condition was 1401 (1005) mm^2 and 72 (22) mm, respectively. In the dual task condition, the mean (standard deviation) elliptical area and edge distance was 1420 (890) mm^2 and 74 (21) mm, respectively. For the younger adults, the mean (standard deviation) task completion time was 17.9 (3.6) seconds and 19.3 (2.9) seconds for the single and dual tasks conditions, respectively. The mean (standard deviation) elliptical area and edge distance for younger adults in the single task condition was 1472 (723) mm^2 and 87 (17) mm, respectively. In the dual task condition for the younger adults, the mean (standard deviation) elliptical area and edge distance were 2169 (2065) mm^2 and 78 (29) mm, respectively. The mean (standard deviation) animal naming rate for the dual task condition was 0.4 (0.2) animals/second and 0.6 (0.2) animals/second for older and younger adults, respectively.

For older adults, task performance (traditional and ladder specific) had significant correlations with the upper arm dexterity and coordination, balance, and cognition domains, regardless of cognitive demand (single task or dual task) (Table 3.1.3). Vision, proprioception, risk-taking and general anxiety were significantly correlated with task performance measures during the single task, but not the dual task condition. The bimanual pole test speed, grip strength and reaction time were significantly correlated with task performance measures in the dual task condition, but not the single task condition.

Table 3.1.3: Correlations between individual measures and task performance measures. Mean (standard deviation) individual measure scores and Pearson's correlations of individual measures with the task performance measures for older adults. Mean values are denoted in standard unit metrics and integers (Int). Pearson's correlation coefficients with the traditional task performance measure (z-score of elliptical area and task time) are shaded and Pearson's correlations with the ladder specific task performance measure (z-score of edge distance and task time) are non-shaded for single and dual task conditions. Individual measures are categorized by domain (vision, proprioception and sensation, upper arm dexterity/coordination and stability, strength, balance, cognition, psychological). Bold values indicate a significant correlation.

			Single task		Dual task	
	Mean (standard deviation)		Traditional	Ladder specific	Traditional	Ladder specific
Vision						
Edge contrast sensitivity	23.3 (1.3)	Int	**0.201***	**0.289****	0.130	0.037
Proprioception & sensation						
Lower limb proprioception	2.2 (1.4)	deg	-0.191	**-0.248***	0.089	0.120
Elbow proprioception	5.2 (2.5)	deg	-0.198	-0.183	-0.183	-0.057
Tactile sensitivity	0.25 (0.18)	g	-0.129	-0.056	-0.191	-0.012
Upper arm dexterity, coordination and stability						
Finger taping	51.5 (5.4)	Int	**0.290****	**0.262****	**0.216***	0.175
Loop & wire	21.9 (13.5)	Int	**-0.297****	**-0.337*****	-0.199	**-0.228***
Bimanual pole test	24.1 (9.5)	s	-0.106	-0.073	**-0.248***	**-0.277****
Arm stability: eyes open	40.7 (14.2)	deg	-0.034	-0.054	0.028	0.060
Arm stability: eyes closed with weight	42.9 (14.3)	deg	0.051	0.015	0.025	0.039
Strength						
Knee strength	35.2 (13.2)	kg	0.124	**0.246***	**0.226***	**0.380*****
Grip strength	25.8 (9.5)	kg	0.026	0.170	0.082	**0.355*****
Balance						
Sway: eyes open, on floor	84 (44)	mm	-0.188	-0.064	-0.151	-0.100
Sway: eyes open, on foam	215 (108)	mm	**-0.327*****	**-0.224***	**-0.338*****	**-0.356*****
Coordinated stability	4.4 (6.6)	Int	**-0.387*****	-0.188	**-0.234***	**-0.290****
Cognition						
Hand reaction time	224 (36)	ms	-0.120	-0.161	-0.171	**-0.253***
Trails A	35.5 (10.4)	s	**-0.372*****	-0.137	**-0.490*****	**-0.281****
Trails B	78.6 (28.3)	s	**-0.357*****	-0.156	**-0.387*****	**-0.230***
Trails B-A	43.2 (24.5)	s	-0.183	-0.061	-0.159	-0.135
Mini-Mental State Exam	28.5 (1.3)	Int	**0.281****	**0.203***	**0.278****	**0.252***
Psychological						
Risk-taking	24.4 (4.8)	Int	**0.283****	0.180	0.069	0.080
GAD-7	1.27 (1.8)	Int	0.080	**0.210***	-0.016	0.030
Icon-FES	14.1 (3.9)	Int	**-0.271****	**-0.259****	-0.126	**-0.219***

$p \leq 0.05$*, $p \leq 0.01$**, $p \leq 0.001$***

Edge contrast sensitivity, upper arm dexterity and coordination, knee strength, balance, cognition and age were significant predictors of task performance across the two task performance measures and two cognitive demands (Table 3.1.4, Figure 3.1.3), confirming Hypothesis 3.1.1.

The traditional task performance measure (z-score of elliptical area and task time) in the single task condition was predicted by the Trails A test (standardized β = -0.327; t_{84} = -3.48), coordinated stability (standardized β = -0.290; t_{84} = -3.07) and edge contrast sensitivity (standardized β = 0.203; t_{84} = 2.20) (model: R = 0.535; $F_{3,84}$ = 11.21) (Figure 3.1.3.a). The addition of age and gender led to significantly improved prediction (r^2 change = 0.077).

The ladder specific task performance measure (z-score of edge distance and task time) in the single task condition was predicted by edge contrast sensitivity (standardized β = 0.312; t_{90} = 3.25) and the loop & wire test (standardized β = -0.268; t_{90} = -2.79) (model: R = 0.454; $F_{2,90}$ = 11.70) (Figure 3.1.3.c). The addition of age and gender did not significantly improve prediction (r^2 change = 0.028).

The traditional task performance measure in the dual task condition was predicted by the Trails A test (standardized β = -0.428; t_{93} = -4.75) and sway: eyes open on foam (standardized β = -0.231; t_{93} = -2.56) (model: R = 0.528; $F_{2,93}$ = 17.96) (Figure 3.1.3.b). The addition of age and gender did not significantly improve prediction (r^2 change = 0.037).

The ladder specific task performance measure in the dual task condition was predicted by knee strength (standardized β = 0.282; t_{93} = 2.87) and sway: eyes open on foam (standardized β = -0.249; t_{93} = -2.53) (model: R = 0.430; $F_{2,93}$ = 10.54) (Figure 3.1.3.d). The addition of age and gender did not significantly improve prediction (r^2 change = 0.038).

Table 3.1.4: Individual measures that predict task performance. Individual measures that best predict traditional (z-score of elliptical area and task time; shaded) and ladder specific (z-score of edge distance and task time; non-shaded) task performance measures in the single and dual task conditions. The *R*- and *F*-values are denoted for the model after the first step (before age and gender were entered). Individual measures are listed in the order they were entered into the model and values are denoted for the model after the first step (above the dashed line). Variables below the dashed line (age and gender) were force entered into the model, denoting values after the second step. The standardized β, *t*-statistic and r^2 change (increase in explained variance by step) for each predictor variable are denoted. Bold values indicate a significant predictor (t-statistic), addition to the model (r^2 change) or model (*F*-value).

Single task				Dual Task			
Traditional	$R = 0.535$; $\mathbf{F_{3,84} = 11.21}$***			**Traditional**	$R = 0.528$; $\mathbf{F_{2,93} = 17.96}$***		
	Standardized β	*t-statistic*	*r^2 change*		*Standardized β*	*t-statistic*	*r^2 change*
Trails A	-0.327	**-3.48*** **	**0.155*** **	Trails A	-0.428	**-4.75*** **	**0.228*** **
Coordinated stability	-0.290	**-3.07** **	**0.090** **	Sway: eyes open, on foam	-0.231	**-2.56***	**0.051***
Edge contrast sensitivity	0.203	**-2.20***	**0.041***	Age	-0.088	-0.85	0.037
Age	-0.247	**-2.45***	**0.077** **	Gender	-0.177	-1.97	
Gender	-0.166	-1.84					
Ladder specific	$R = 0.454$; $\mathbf{F_{2,90} = 11.70}$***			**Ladder specific**	$R = 0.430$; $\mathbf{F_{2,93} = 10.54}$***		
	Standardized β	*t-statistic*	*r^2 change*		*Standardized β*	*t-statistic*	*r^2 change*
Edge contrast sensitivity	0.312	**3.25** **	**0.138*** **	Knee strength	0.282	**2.87** **	**0.128*** **
Loop & wire	-0.268	**-2.79** **	**0.068** **	Sway: eyes open, on foam	-0.249	**-2.53***	**0.056***
Age	-0.168	-1.76	0.028	Age	-0.240	**-2.11***	0.038
Gender	0.038	0.38		Gender	0.057	0.52	

$p \leq 0.05$*, $p \leq 0.01$**, $p \leq 0.001$***

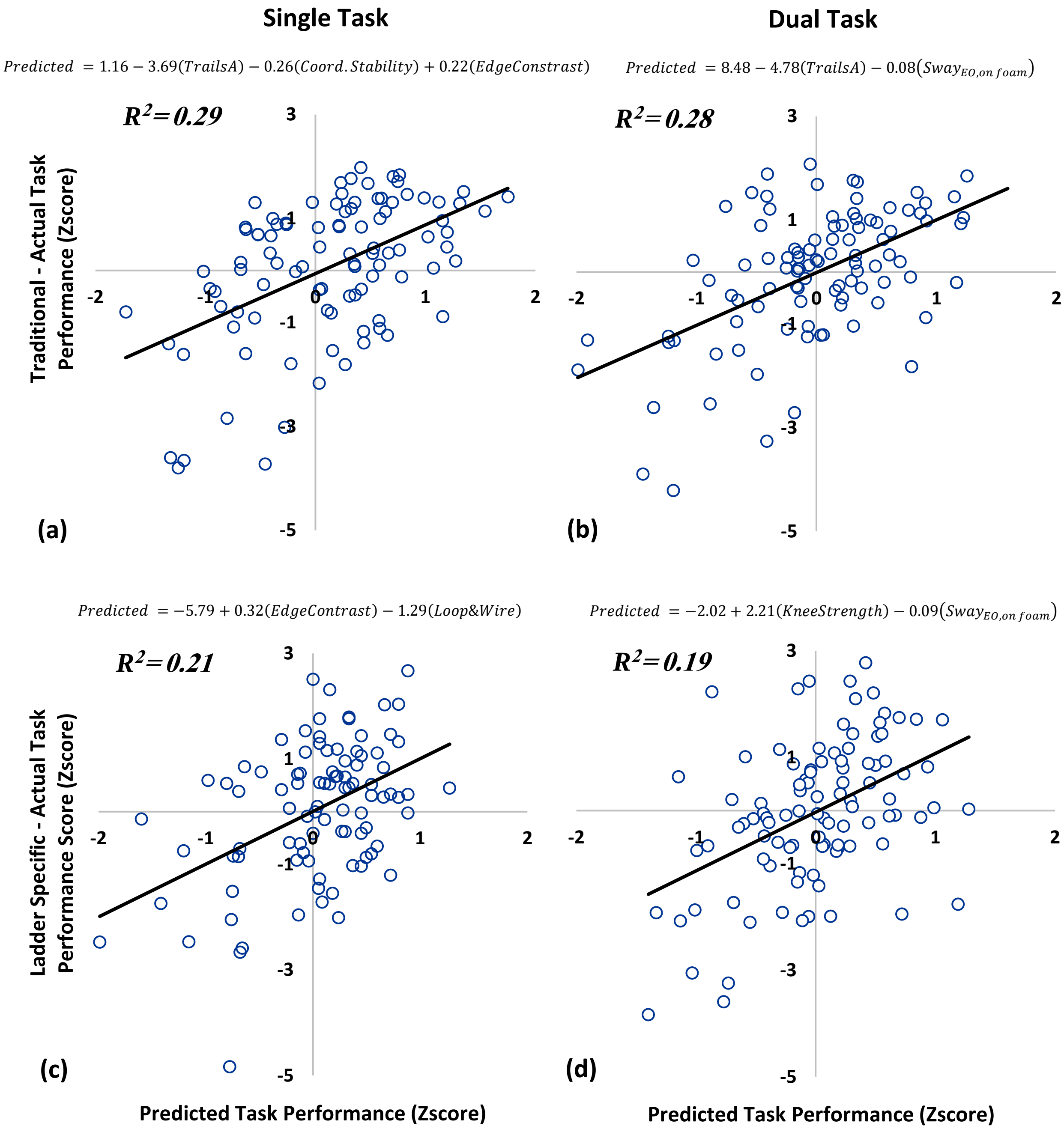


Figure 3.1.3: Linear regression models of task performance. Predicted task performance (x-axis) plotted with actual task performance (y-axis) from linear regression models of traditional (a, b) and ladder specific (c, d) task performance during single (a, c) and dual (b, d) task conditions. Linear regression equations for predicted task performance are displayed on each plot utilizing unstandardized β values. The R^2 value of each model is displayed on each plot. Bold R^2 values denote a statistically significant model.

A similar elliptical area was observed for older adults and younger adults ($F_{1,113} = 3.23$; $p = 0.075$) (Figure 3.1.4.a). Cognitive demand ($F_{1,113} = 2.54$; $p = 0.116$) and the interaction between age group and cognitive demand ($F_{1,113} = 1.02$; $p = 0.315$) were not found to influence elliptical area. A greater edge distance was observed for younger adults than older adults ($F_{1,112} = 4.84$; $p = 0.030$) (Figure 3.1.4.b). Cognitive demand did not influence edge distance ($F_{1,112} = 2.14$; $p = 0.146$), but an interaction between age group and cognitive demand was found with edge distance ($F_{1,112} = 4.98$; $p = 0.028$) (Figure 3.1.4.b). A greater task completion time was observed for older adults ($F_{1,120} = 22.76$; $p < 0.001$) and during the dual task condition ($F_{1,120} = 12.67$; $p = 0.001$) compared to younger adults and the single task condition (Figure 3.1.4.c). No interaction between age group and cognitive demand was present with task completion time ($F_{1,120} = 0.23$; $p = 0.634$). Males had a greater elliptical area ($F_{1,114} = 27.15$; $p < 0.001$), but took less time to complete the task ($F_{1,120} = 6.03$; $p = 0.015$) compared to females. Gender was not found to influence edge distance ($F_{1,113} = 0.03$; $p = 0.870$). Younger adults had a faster animal naming rate than older adults ($t_{121} = 4.90$; $p < 0.001$) (Figure 3.1.4.d). A greater difference in standing stability (edge distance) between cognitive demands was observed in younger adults, but not for older adults, in opposition of Hypothesis 3.1.2.

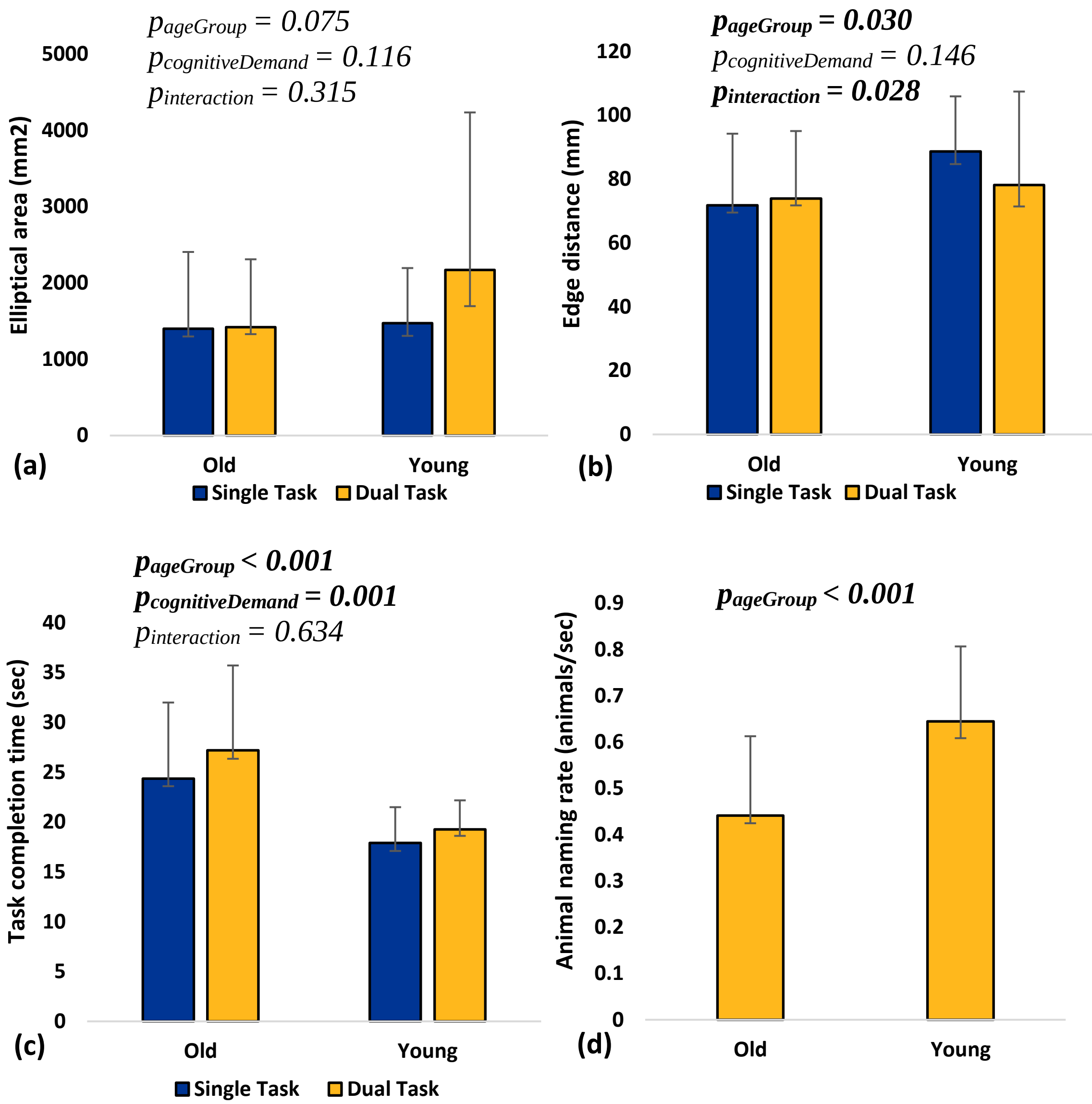


Figure 3.1.4: Standing stability and task competition measures by age group and cognitive demand. The elliptical area (a), edge distance (b), task completion time (c) and animal naming rate (d) for older and younger adults during the single (blue bars) and dual (yellow bars) task conditions. Positive error bars represent the standard deviation and negative error bars represent standard error. Bold *p*-value denote significant differences between age group, cognitive demand or the interaction between age group and cognitive demand.

3.1.5 Discussion

3.1.5.1 Part 1: Individual measures on ladder task performance

This study found individual measures to influence task performance of older adults during ladder use. Specifically, edge contrast sensitivity, upper arm dexterity and coordination, knee strength, balance, cognition and age of older adults predicted task performance (traditional or ladder specific, single or dual task) of ladder use.

3.1.5.1.1 Predictors of ladder task performance

The predictors of task performance were categorized into three tiers: primary predictors, secondary predictors with consistent associations, and secondary predictors with inconsistent associations (Table 3.1.5). Regardless of task performance measure (traditional or ladder specific) and cognitive demand (single or dual task), balance (assessed from clinical measures) was a primary predictor of safe and effective ladder use (a predictor of task performance in three out of the four models) and consistently correlated with task performance. Cognition, upper arm dexterity and coordination, and age were predictors of task performance in at least one model and were significantly correlated with task performance across all conditions, signifying a strong association of these measures with safe and effective ladder use. Edge contrast sensitivity and knee strength were also predictors of task performance in at least one model, but were not always correlated with task performance.

Table 3.1.5: Top predictors of task performance. Individual factors that are predictors and associated with task performance of ladder use. The strength of each factor is separated by three levels: primary predictors, secondary predictors and consistent associations, and secondary predictors and inconsistent associations.

Predictors of Ladder Task Performance
Primary predictors
Balance measures
Secondary predictors and consistent associations
Cognitive measures
Upper arm dexterity and coordination
Age
Secondary predictors and inconsistent associations
Edge contrast sensitivity
Knee strength

These findings agree with previous literature that has found sway, cognition and strength to be the best predictors of dynamic stability measures [99]. Sway with eyes open on foam was well correlated with all task performance measures across the single and dual task demand, while cognition measures (e.g. hand reaction time, Trails A, Trails B, Mini-Mental State Exam) were significantly correlated with all task performance measures by cognitive demand. Similarly, the upper arm dexterity and coordination measures (finger tapping, loop & wire, bimanual pole test) require fast and accurate movements [109], and are likely reflected in the standing stability and the time required to complete the task. At least two upper arm dexterity and coordination measures were significantly correlated with each task performance measure by cognitive demand, and the loop & wire test was a predictor in one of the models (ladder specific – single task). Furthermore, knee strength was a predictor in one of the models (ladder specific – dual task) and correlated with all task performance measures expect one (traditional – single task).

In the majority of models, age and gender did not significantly improve predictability on task performance. This indicates that our clinically assessed individual measures captured the salient aspects of age and gender on task performance in most cases (Appendix B.2.2, Appendix

B.2.3). However, in one of the models, there was an additional element of aging that was not captured by clinically assessed measures (i.e. clinical assessments on physical and cognitive capabilities and psychological outlook could not account for all deficiencies due to aging). Age as a predictor of safe and effective ladder use agrees with the vast amount of literature that shows an increase in falls, ladder falls and fall risk with age [2, 32, 113].

Interestingly, edge contrast sensitivity was significantly correlated with task performance during the single task, but not the dual task condition. Individuals may have a limited amount of cognitive resources that become more apparent during dual task paradigms, especially among older adults [102]. Resource competition is known to occur across sensory systems and cognition demand [121], potentially limiting attentional resources towards visional processes. This may have reduced the influence of edge contrast sensitivity on task performance during the dual task condition. However, additional work is needed to confirm the relationship between sensory systems and cognitive demand on ladder task performance.

3.1.5.1.2 Single task

The two task performance measures (traditional and ladder specific) yielded similar and different predictors during the single task condition. Both task performance measures were predicted by edge contrast sensitivity. However, the traditional task performance measure was also predicted by cognition (Trails A), balance (coordinated stability) and age. The ladder specific task performance measure was additionally predicted by upper arm dexterity and coordination (i.e. loop & wire test). The differences in predictors may be attributed to the standing stability definition. While elliptical area and edge distance are somewhat correlated ($\rho = -0.309$; $p < 0.001$) (Appendix B.2.4), large variations in COP movement in any direction results in greater elliptical area, and greater COP movement only in the posterior direction results in a shorter edge distance.

Good performance in coordinated stability requires controlled and accurate movements from the lower body [99]. Thus, these controlled movements are likely to reflect less variable COP movements, resulting in a smaller COP elliptical area and better task performance score. Cognition is a critical component of both task performance measures, but the Trails A test was not significantly correlated with the ladder specific task performance measure during the single task condition. Furthermore, controlled upper limb movements (i.e. loop & wire test) was found to be significantly correlated with both task performance measures in the single task condition, but the loop & wire test was only a predictor in the ladder specific task performance model and not the traditional task performance model.

3.1.5.1.3 Dual task

Under the dual task condition (naming animals while changing a light bulb), the predictor variables across task performance had one similarity. Specifically, both task performance measures were predicted by balance (i.e. sway: eyes open, on foam). Standing sway measured by traveled path length is well correlated with COP standing stability measures [122]. Yet, standing balance in a challenging environment (sway: eyes open on foam) may be more reflective of standing stability during ladder use, especially during the dual task condition. Standing balance alone (sway: eyes open, on floor) was not correlated with ladder task performance. Standing on foam requires additional cognitive resources to reweight sensory inputs and maintain balance. Similarly, maintaining balance while changing a light bulb at an elevated height requires more cognitive resources than quiet standing on the floor, especial with additional cognitive loading (i.e. naming animals). Cognitive processing speed (i.e. Trails A test) was an additional predictor of the traditional task performance measure during the dual task condition. This speed-based assessment is likely related to the task completion side of the task performance metric. Cognitive processing speed was also correlated with the ladder specific task performance measure during the dual task condition but was not a predictor in the final model. Knee extension strength was an additional predictor of the ladder specific task performance measure, but was also correlated with the traditional task performance measure during the dual task condition. Knee strength is not only correlated to maximum lean distance, but also directed waist movements (i.e. coordinated stability) [99]. Greater knee strength of participants in this study may facilitate more anterior and controlled COP movements, resulting in a greater edge distance and a reduced elliptical area, respectively.

3.1.5.1.4 Limitations

This study has some noteworthy limitations. We based our task performance measures on task completion time and standing stability (via traditional or ladder-specific balance measurements). While we believe our task performance measures are reflective of safe and effective ladder use, this study did not assess these measures with ladder fall outcome. Additional work is required to determine if this task performance metric is associated with ladder fall risk. We assessed 23 individual measures across 7 categorical domains (vision, proprioception, upper arm dexterity/coordination and stability, strength, balance, cognition, psychological), but there may be alternative individual measures that predict ladder task performance. We tested task performance of individuals changing a light bulb on a household stepladder. Future research is required to determine individuals measures that influence ladder task performance across different tasks and ladder designs.

3.1.5.1.5 Conclusions

This is the first study to assess individual factors of older adults on safe and effective ladder use. We found balance to be a primary predictor of task performance while changing a light bulb on a household stepladder. Furthermore, cognition, upper arm dexterity and coordination, edge contrast sensitivity, knee strength, and age are secondary predictors of ladder task performance. This knowledge can be used to guide ladder fall interventions. Such interventions may be in the forms of screenings, ladder redesign and safety instruction. For example, individuals can be screened for ladder fall risk from individual measures that are associated with safe and effective ladder use (i.e. task performance). Ladders can be redesigned to reduce the need of balance and knee strength via a forward lean support and increased based of support for standing/working on a stepladder. Safety instructions can be updated to inform users to not work on the ladder while distracted and to utilized additional tools to avoid strenuous upper arm postures that require increased dexterity and coordination. Therefore, knowledge of individual factors that influence ladder task performance in this study can aid in reducing ladder fall injuries.

3.1.5.2 Part 2: Ladder use by age group

This study did not find older adults to show a greater change in standing stability across cognitive demand, but a greater change is standing stability with younger adults across cognitive demand. Overall, younger adults displayed a greater edge distance, a reduced task completion time, and faster animal naming rate than older adults across both cognitive demands. Elliptical area between younger and older adults was similar. Cognitive demand influenced the task completion time, but not the standing stability measures of younger and older adults in this study.

3.1.5.2.1 Edge distance

We did not find older adults to display a large change in standing stability with additional cognitive loading. Surprisingly, we found younger adults to display a greater change in standing stability with additional cognitive loading. Specifically, younger adults reduced their distance from the ladder step edge by 11 mm from the single to the dual task condition. Older adults minimally changed their edge distance between cognitive demands (2 mm difference). Overall, younger adults displayed a greater edge distance than older adults by 17 mm and 4 mm for the single and dual task, respectively. This difference is meaningful to the base of support, representing up to 24% of the remaining posterior edge distance for older adults. This suggests that older adults exhibit more risky standing posture on a stepladder and may be more likely to experience a ladder fall from backward balance loss.

3.1.5.2.2 Elliptical area

Elliptical area was similar between younger and older adults. During the single task condition, younger adults (1472 mm^2) exhibited a slightly greater elliptical area than older adults (1401 mm^2). During the dual task condition, younger adults (2169 mm^2) had a greater elliptical area than older adults (1420 mm^2), but the difference was not significant due to the large variability among younger adults. High variability of younger adults in the dual task condition was not expected, thus, testing additional younger adults may lead to a more clear understanding. Older adults may exhibit a slightly more cautious or rigid standing posture during ladder use, but the difference was not significantly different from younger adults in this study. Notably, rigidity in posture from muscle co-contraction is associated with decreased stability [123, 124]. Thus, elliptical area alone may not reflect fall risk for those who adopt a rigid stance.

3.1.5.2.3 Overall stability

Overall, older adults displayed cautious (or rigid) and risky standing behavior when compared to younger adults. Such that a smaller elliptical area reflects a more cautions or rigid stance, but a smaller edge distance reflects an increased risk in backward balance loss. This is similar to ladder climbing research that has found younger adults to experience more ladder climbing slips (indicating less cautious climbing), but climb with their body closer to the ladder (indicating safer and more controlled climbing) than older adults [80]. Younger adults may experience more perturbations (i.e. loss of balance and near miss falls) during ladder use, but are likely to more effectively detect and respond to perturbations to avoid a fall [125]. Declines in individual measures with aging may be more apparent when assessing edge distance. Specifically, older adults may be less aware they are approaching the ladder step edge (reduced proprioception); have reduced control in upper (reduced performance in loop & wire test) and lower (increased sway with eyes open on foam) body movements, reducing stability in COP measurements; or lacking in muscle strength (from the knee) to lean forward during ladder use. Furthermore, psychological measures are also known to impact standing stability. Specifically, anxious individuals show a reduced elliptical area at elevated levels [100], and are known to lean forward more during dual task conditions [126]. These individual measures may assist in explaining differences in stability between younger and older adults, and are supported by Hypothesis 3.1.1 and correlations between individual measures and task performance measures in this study (Table 3.1.3). While older adults may be slightly more cautious (reduced elliptical area), they may also be more likely to experience backwards balance loss (shorter edge distance) during ladder use. Thus, this work suggests older adults to be at potentially higher risk of experiencing a ladder fall injury.

3.1.5.2.4 Additional tasks

Older adults performed worse than younger adults when completing a task on a household stepladder in the single and dual task conditions. The older adults took more time to complete the task and named less animals in the dual task condition than younger adults. This may be due to a combination of resource completion and task prioritization. We have a limited amount of cognitive resources to complete tasks, and this threshold is lower for older adults [102]. Older adults may have less resources than younger adults to maintain balance while completing additional tasks (changing a light bulb and naming animal) and/or may prioritize balance over other tasks. Furthermore, older adults may be slower than younger adults when changing a light bulb and naming animals, even without using a ladder. Minimal changes in standing stability measures between cognitive demands, suggest older adults to prioritize balance over naming animals (dual task) because their standing stability did not significantly worsen. This is similar to previous research that has found older adults to prioritize balance at elevated levels over a secondary task [101]. Notably, this increase in time leads to a greater exposure duration to ladder use, increasing ladder fall risk. In addition, prolonged ladder use can lead to fatigue, reducing standing stability. Resource competition was apparent in both age groups, as the dual task condition resulted in a longer task time for both age groups. Furthermore, the standing stability of younger adults worsened in the dual task conditions, suggesting younger adults to prioritize the dual task of naming animals over their balance.

3.1.5.2.5 Limitations

This analysis has limitations. The primary goal was to compare ladder use of older adults relative to younger adults. Thus, 104 older adults were recruited, and 20 younger adults were recruited as controls. High variability in standing stability measures were present among younger adults. Thus, future studies should consider recruiting a larger sample of younger adults to better understand their standing stability during ladder use. This study only assessed two measures of standing stability, and alternative stability measures may yield different results. This study only assessed ladder use for changing a light bulb on a household stepladder. Future studies should investigate ladder use across different tasks and ladder designs.

3.1.5.2.6 Conclusions

This study compared standing stability measures and task completion time of ladder use between older and younger adults. While older adults exhibit some caution in their stance during ladder use, they are at greater risk of backward balance loss and have increased time in ladder exposure length than younger adults. This suggests older adults to be more likely to experiencing a ladder fall injury. Additional cognitive loading was found to affect younger and older adults. Older adults were found to prioritize their balance over the additional task. Younger adults performed better than older adults in completing the additional tasks, but their balance worsened under additional cognitive loading. This suggests that younger adults prioritize the additional task over balance. This knowledge reveals the influence of environmental demands on safe and effective ladder use across different age groups. Understanding these effects across age groups can guide ladder fall interventions that are best suited for younger and older ladder users. Thus, this work can aid in reducing ladder fall injuries across our diverse population.

4.0 Individual, Environmental and Biomechanical Response Factors on Fall Recovery after a Ladder Climbing Perturbation

This chapter is divided into three sections. The sections investigate individual and environmental factors (4.1: climbing direction, gloves, gender, adaptation), individual and biomechanical response factors (4.2: upper body strength, hand placement, foot placement) and biomechanical response factors (4.3: hand-rung forces) after a ladder climbing perturbation. Sections 4.1 [127] and 4.2 [128] have been published and granted permission/acknowledged to be presented in this dissertation (Appendix C.1). Section 4.3 has been submitted for publication in the Journal of Biomechanics in recognition of Dr. Pliner's Pre-doctoral Young Scientist Award from the American Society of Biomechanics [129]. Preliminary results for Section 4.3 have been published through conference abstracts [130, 131]. Additional tables/figures (Table 4.1.1, Table 4.2.1, Figure 4.1.2) have been added to these sections to increase study clarity. Additional study clarifications (Appendix C.2), methodology (Appendix C.3), and supplementary analyses (Appendix C.4) can be found in Appendix C.

4.1 Factors Affecting Fall Severity from a Ladder: Impact of Climbing Direction, Gloves, Gender and Adaptation

4.1.1 Abstract

Ladder falls cause many fatal injuries. The factors that affect whether a ladder perturbation leads to a fall are not well understood. This study quantified the effects of several factors on a person's ability to recover from a ladder perturbation. Thirty-five participants each experienced six unexpected ladder missteps, for three glove conditions (bare hands, high friction, low friction) and two climbing directions (ascent, descent). Fall severity was increased during ladder descent. Gloves did not affect fall severity. Females compared to males had greater fall severity during ascent and descent. During ascent, females had greater fall severity during the second perturbation but similar fall severity to males during the other perturbations. Additional protection may be needed when descending a ladder. Also, females may benefit from targeted interventions like training. This study does not suggest that gloves are effective for preventing ladder falls

4.1.2 Introduction

Ladder falls are the leading cause of fatal falls [26] and 63 percent of ladder injuries result in a fracture or sprain [132]. Nearly half of these ladder fall-related fractures lead to over $5,000 in medical cost per case [39]. However, these severe injuries are believed to be preventable through safer ladder climbing practices [33, 42]. Identifying the climbing practices associated with reduced fall risk and the individuals at risk for falling is important to develop and target strategies for reducing the number of people who suffer from ladder fall injuries.

Ladder falls can be broadly categorized into falls from ladders and falls with ladders [44]. A fall with a ladder is typically a result of unstable ladder placement [39, 44, 58]. Instability in the ladder placement can cause the ladder to tip or the base to slide. Therefore, prevention strategies for falls with ladders have focused primarily on securing the ladder [58], improving friction between the ladder base and ground surface [53] or optimizing the inclination angle of extension ladders [51]. A fall from a ladder is the result of the climber losing their supporting hand and/or foot contact with the ladder (e.g. slip of the hand or foot). A majority of falls from ladders result from a climber's overbalance, slip, or misstep [44]. The ladder design and biomechanics of ladder climbing have been found to be associated with slip propensity and a climber's ability to recover from a slip [80, 82]. The present study aims to expand on this research to identify factors that affect a person's ability to recover after a ladder climbing perturbation.

Epidemiology research has suggested that climbing direction (ascent/descent) may be an important risk factor for falls from ladders. A review of mining injury reports revealed that ladder fall injuries occur three times more often for miners exiting (and thus descending ladders) mining equipment compared with entering equipment [27]. One explanation that was offered by the authors of this study is that miners may have poorer balance during descent due to the amount of vibration exposure that is experienced between ascent at the start of a shift and descent at the end of the shift [27]. However, previous research has suggested that exposure to vibration does not have substantial short-term impacts on balance [133, 134]. An alternative hypothesis is that more falls are experienced during ladder descent because recovering from a perturbation during descent is more challenging than ascent due to the body's downward momentum. Although injury records show more descending ladder falls than ascending, a gap in the literature exists regarding whether this is because of some exposure that typically occurs between ascent and descent or because recovering from a perturbation during descent is more challenging.

Glove use has also been suggested to be an important risk factor for recovery after a climbing perturbation since glove use affects friction and tactile perception. The use of gloves is known to impact the achievable forces between a hand and a handle, which is believed to affect a person's ability to recover from a ladder climbing perturbation [83, 85, 86]. Specifically, the coefficient of friction (COF) between the rung and hand is positively correlated with the amount of frictional force that can be applied to a rung before the rung is pulled out of the hand's grasp [85]. Also, a low COF between the glove and rung has been associated with an increase in the muscular effort required to stabilize a sudden upward impulse force applied to a rung [86]. However, previous studies that examined the impact of friction on recovery from a ladder perturbation only considered the interaction between the hand and the rung in a stationary position [83, 85, 86] without consideration of the role that the rest of the body plays after a ladder perturbation. This method may be an over-simplification of the effects that gloves have between the hand and rung during an actual ladder fall. Thus, additional research is needed to determine if these changes in force application translate into improved ability to recover from a ladder perturbation.

Contradicting evidence exists regarding if whether gender has an impact on ladder fall severity. Differences across genders in anthropometry and strength may lead to different capacities for reaching rungs and applying the required forces, which could then have an impact on fall severity. Females have less upper body strength than males [135] even after normalizing for body mass [87] and increased upper body strength is believed to be critical to prevent a ladder fall [85]. Also, females are shorter in stature, have shorter arms and tend to have smaller hand sizes [136], which may impact their ability to reach and grasp ladder rungs. Previous research found females to have a lower grip force than males, which is partially due to their smaller hand size [137, 138]. Yet, male workers account for the majority of ladder fall injuries, have higher ladder fall incidence rates [42], and incur more severe ladder fall injuries than female workers [35]. These epidemiology studies should be interpreted cautiously since they may be affected by gender differences in the frequency of using ladders during work. Thus, controlled laboratory studies may provide better characterization of the effects of gender on ladder falling risk.

Repeated perturbations to a ladder climber have not been studied to quantify the adaptation process. In gait perturbation studies, participants have been found to alter their gait biomechanics when perturbed repeatedly (i.e. by shifting their center of mass anteriorly, reducing foot angle, increasing knee angle, and decreasing trunk angle) [139, 140]. These adaptations can be made before or after perturbation onset [139], and are correlated with increased stability [139] and potential fall avoidance [140]. In addition, adaptation changes have also been noticed in participants anticipating a slip during gait [141]. Similarly, a person's ability to recover from a perturbation and avoid a fall may change after repeated exposures to a ladder perturbation.

The purpose of this study is to determine the impacts of climbing direction, gloves, gender and adaptation on fall severity following a ladder perturbation. This study will test the following hypotheses.

Hypothesis 4.1.1: Falls during ladder descent will result in more severe fall outcomes compared to ladder ascent.

Hypothesis 4.1.2: The use of gloves will affect fall severity outcomes.

Hypothesis 4.1.3: Female ladder climbers will have more severe fall outcomes following a perturbation than their male counterparts.

Hypothesis 4.1.4: Fall severity will vary with continuing perturbations.

4.1.3 Methods

4.1.3.1 Participants

Thirty-five healthy participants between the ages of 18 and 29 years were recruited. The sample comprised 22 males (23.8 ± 5.3 yrs., 80.6 ± 7.8 kg, 1.8 ± 0.1 m) and 13 females (25.5 ± 6.0 yrs., 63.3 ± 6.6 kg, 1.7 ± 0.1 m). Exclusion criteria included musculoskeletal disorders, previous shoulder dislocations, osteoporosis/osteoarthritis, neurological/cognitive disorders, balance disorders and pregnancy. This study was approved by the University of Wisconsin-Milwaukee Institutional Review Board (Protocol Number: 11.366) and all participants signed informed consent prior to participation.

4.1.3.2 Instrumented ladder

A vertical 12-foot custom-designed ladder was secured in the middle of the motion capture volume (Figure 4.1.1). The ladder had twelve cylindrical rungs, which were 32 mm (1.25 in) in diameter and spaced 305 mm (12 in) apart, in compliance with U.S. Occupational Safety and Health Administration (OSHA) standards [92]. All rungs excluding the fourth rung were equipped with two strain gauges that were sampled at a frequency of 2000 Hz. The strain gauges were located at the bottom and the side of the rung facing the climber, positioned in the center. To ensure all participants experienced the same climbing perturbation, a ladder misstep was created by a mechanical release, based-off of a specific event in the individual's climbing cycle. A simulated misstep perturbation was induced on the fourth rung (referred to as the releasing rung hereafter) by releasing the rung under the foot during climbing. The left and right side of the releasing rung had a spring-loaded connector inside the rung. A rod was used to compress each spring-loaded connection to attach the releasing rung with the ladder. The rod and spring connection was held in place with electric magnets during baseline climbing. When the releasing rung was triggered to decouple from the ladder, the magnets would demagnetize and the springs would extend, breaking the rungs connection with the ladder. The releasing rung was programmed to decouple when less than five percent of the participant's body weight remained on the previous rung (i.e. foot-off of the leg contralateral to the perturbation leg). Foot-off of the leg contralateral to the perturbation leg was selected as the perturbation time, based on previous research that found that this is typically the time when the foot slips off of a rung [82]. Prior to testing, participants were informed they would be climbing stable and unstable ladders, but they were not informed of the perturbation mechanism and location.

Figure 4.1.1: Instrumented ladder. The ellipse encircles the electronically-controlled releasing rung.

4.1.3.3 Testing session

The testing session was started by recording the mass and height of the participant. The participant was equipped with climbing attire, footwear, shin guards and a safety harness. The footwear was a standard work shoe with a rubber sole and raised heel. The shin guards acted as additional protection to the climber in case their legs contacted the ladder after the perturbation. The safety harness was equipped with a load cell, which collected force data at a frequency of 1000 Hz to measure the weight supported by the harness. Forty-seven reflective markers were placed on the participant's anatomical landmarks for the head (3 markers), torso (10 markers), upper extremities (14 markers) and lower extremities (20 markers) (Appendix C.3.2, Appendix C.3.3). Only the bilateral anterior superior iliac spine (ASIS) and posterior superior iliac spine (PSIS) torso markers were analyzed in this study. Markers were recorded by 13 motion capture cameras at a frequency of 100 Hz (Motion Analysis Raptor Corp., Santa Rosa, CA) (Appendix C.3.4). In a single testing session, participants were perturbed three times while ascending and three times while descending the ladder out of 30 total ascent and descent trials. The perturbations were conducted once in each climbing direction (ascent and descent) for each of three different glove conditions (bare hands, latex-coated gloves and cotton gloves). The latex-coated gloves was selected as a high friction glove condition whereas the cotton gloves were selected as a low friction glove condition [85]. Both gloves were bought off-the-shelf. High friction gloves were made of knitted fabric with a latex palm (HD30503/L3P, West Chester, Inc., Monroe, OH) and low friction gloves were made of 100% cotton (COTPR, Drillcomp, Inc., New Hope, PA) (Appendix C.3.5). The high friction gloves were 1.57 mm thick and the low friction gloves were 0.31 mm thick. Three glove sizes were available for the high friction and low friction gloves to accommodate different hand sizes. Perturbation order was randomized. Participants acclimated to the ladder with each glove condition prior to data collection. Three to six regular climbing trials were collected prior to each perturbation to reduce anticipation of the perturbation [80]. Rest time of approximately two minutes was allotted after each perturbation. Participants were instructed to climb at a “comfortable but urgent pace” to simulate climbing speed of a regular-to-busy workday. To ensure participant safety, each participant had an impact mat at the bottom of the ladder, a spotter and belayer.

4.1.3.4 Data analysis

Fall severity to a ladder perturbation was measured by the load cell that was attached to the safety harness. A high harness force was associated with a more severe fall and a low harness force was associated with a less severe fall [142]. The harness force was normalized to each participant’s body weight. Therefore, fall severity was analyzed as a continuous variable and defined as the peak harness force (referred to as harness force hereafter) found across a period of time that represented the time from perturbation onset (start of fall) until the time when the person had either fallen into the harness or had arrested the fall (end of fall). The start of fall was defined as the time that the releasing rung was triggered to decouple from the ladder. The end of fall was defined as the first local maximum in harness force after the first minimum of mid-hip joint center's downward vertical displacement. This method was selected based on initial observations in the harness force data where the peak harness force was typically observed either just before or shortly after the local minimum in hip elevation (Figure 4.1.2). Mid-hip joint centers were calculated using Bell's Method and the ASIS and PSIS markers [143] (Appendix C.3.7). Trials were excluded (43 out of 210 trials) due to technical equipment error (26 trials), participant withdrawal (8 trials), and incongruence between the end of fall time calculated by the algorithm versus the time identified by visual inspection (9 trials) (Appendix C.3.1).

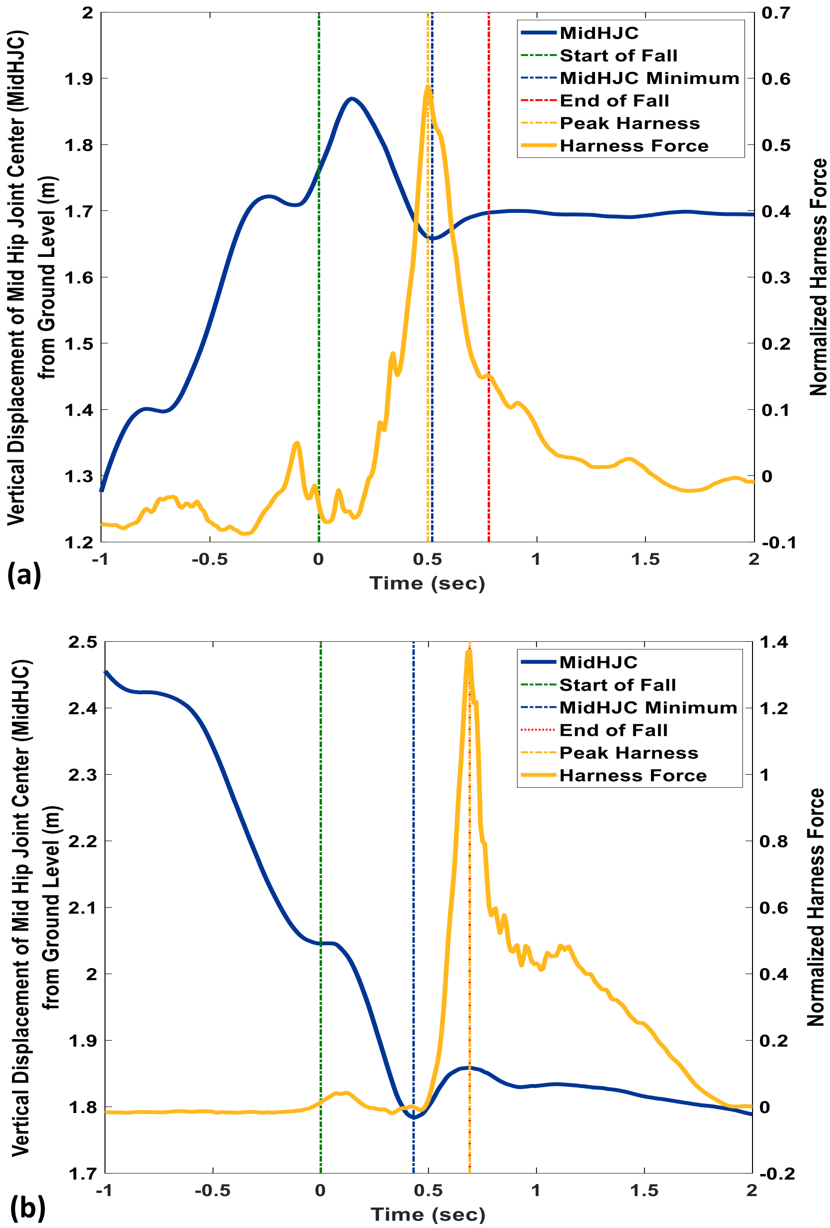


Figure 4.1.2: Time window of peak harness force. The vertical displacement of the mid-hip joint center (MidHJC, solid blue line) and harness force (solid yellow line) over time, where time zero is the start of fall (pertubation onset, represented by a vertically dashed green line). Time of minimum MidHJC (dash blue line), peak harness force (dashed yellow line) and end of fall (first local maximum in harness force after the first minimum in MidHJC, dashed red line) are represented by vertical lines. Peak harness force occuring before a minimum in MidHJC for an ascending pertubation (a) and peak harness force occuring after a minimum in MidHJC for a descending pertubration (b) are depicted. When peak harness force occurs after a minimum in MidHJC, time of peak harness force and end of fall occur at the same time.

The velocity of climber's mid-hip joint center was also quantified at the time of perturbation onset and the time of peak downward velocity between the start of fall and end of fall in order to characterize the momentum of the body. These measures were intended to explain differences in the body's momentum between ascent and descent. A more downward (negative) mid-hip joint center velocity was indicative of greater fall severity [120, 144, 145].

Climbing cycle time was quantified to assess anticipation of the perturbation. This temporal parameter is similar to another study that identified changes in stance duration during slip-anticipation gait trials [141]. Cycle time was calculated from the baseline trial prior to each perturbation trial. Cycle time was defined as the time period from foot contact on the third rung to foot contact on the fifth rung for ascending perturbations and vice versa for descending perturbations. Foot contact was determined from strain gauge data on the rungs captured in the vertical direction and filtered using a zero-phase 4th order Butterworth low-pass filter with a cut-off frequency of 36 Hz [146]. Foot contact was defined as the point in time when strain activity exceeded 10% of the peak strain activity on the corresponding rung during the baseline trial.

4.1.3.5 Statistical analysis

Two primary statistical analyses were used to determine the effect of climbing direction (first analysis) and the other predictor variables (glove condition, gender, perturbation number; second analysis) on harness force (proxy of fall severity). A repeated measures ANOVA was performed with normalized harness force as the dependent variable; while participant number (random), perturbation number (nominal) and climbing direction were the predictor variables (first primary analysis). Perturbation number was added to the model to adjust for potential confounding effects due to participants adapting to the multiple perturbations. Gloves and gender were not included in the first model because ladder ascent and descent were determined to be fundamentally different tasks and, therefore, it was determined that the effects of gloves, gender and adaptation should be assessed for ascent and descent separately. Additionally, to assess the body's momentum between climbing direction, repeated measures ANOVAs were performed with the mid-hip joint center velocity at perturbation onset and peak downward velocity as the dependent variables. Consistent with the first ANOVA, participant number (random), perturbation number (nominal) and climbing direction were the predictor variables. The second primary analysis was a generalized linear model with normalized harness force as the dependent variable and perturbation number (nominal), glove condition, gender, and first order interactions as the predictor variables. Models were performed separately for ascent and descent. In addition, first order interactions that did not occur for every condition were removed (e.g. participant number x gender). A square root transformation was needed to ensure that harness force was normally distributed for both analyses. A significance level of 0.05 was used. Post-hoc comparisons were made using Tukey HSD tests for any primary effects with more than two categories. Given the large number of combinations for the interaction effects between gender and perturbation number (12 combinations for gender x perturbation number), t-tests using a Bonferroni correction (0.05/6) were performed that only considered differences across gender for each perturbation number (i.e. differences between male and female for perturbation 1, 2, 3, etc.). This limited post-hoc test reduced the number of comparisons from 12 to 6 in order to provide sufficient power for describing this interaction. Additionally, a repeated measures ANOVA was run with cycle time as the dependent variable and participant number (random) and perturbation number (nominal) as the dependent variables. Separate analyses were run for the two separate climbing directions (Table 4.1.1). Statistical software (JMP®, Version 13. SAS Institute Inc., Cary, NC.) was used to perform the analyses.

Table 4.1.1: Statistical analyses. The dependent and predictor variables in each statistical analysis. Additional test details are noted (separated test, random and confounding variables). ANOVA 1 and the generalized linear regression are the primary analyses to test the study hypotheses. ANOVAs 2 & 3 are secondary analyses.

Analysis	Separated by	Dependent variable	Predictor variable	Other variable
ANOVA 1	NA	Harness force	Climbing direction	Participant number (random), perturbation number (confounder)
Generalized linear regression	Climbing direction	Harness force	Glove condition, gender, perturbation number, interactions	NA
ANOVA 2	NA	Mid-hip joint center velocities	Climbing direction	Participant number (random), perturbation number (confounder)
ANOVA 3	Climbing direction	Climbing cycle time	Perturbation number	Participant number (random)

4.1.4 Results

Climbing direction was found to have a substantial impact on harness force (proxy of fall severity). The mean normalized harness force (standard deviation) observed in this study across all trials was 0.288 (0.258). Descending perturbations led to harness forces more than double those of ascending perturbations, which confirmed Hypothesis 4.1.1 ($p < 0.001$, $F_{1,132} = 65.33$) (Figure 4.1.3). Harness force did not significantly change across the six perturbations ($p = 0.078$, $F_{5,132} = 2.03$) in the ANOVA.

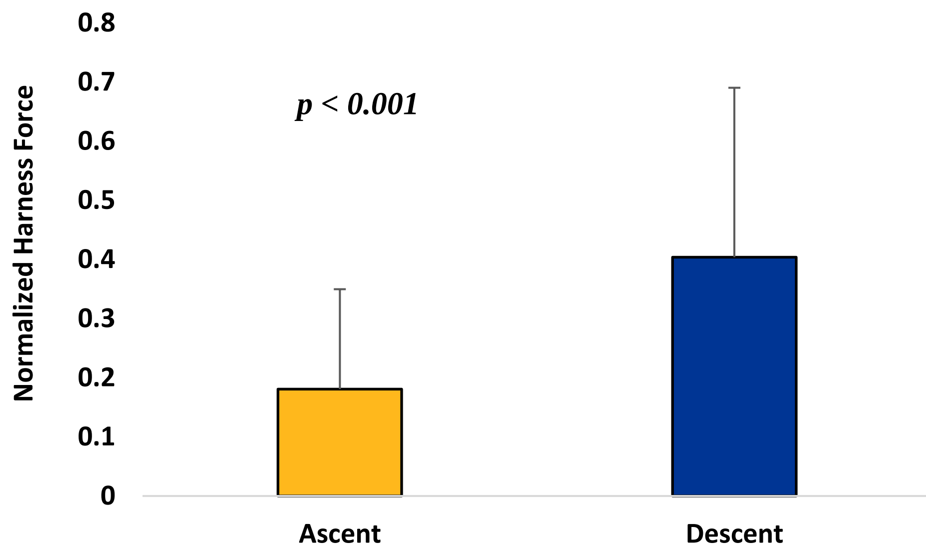


Figure 4.1.3: Harness force by climbing direction. The mean normalized harness force after an ascending and descending climbing perturbation. Error bars denote standard deviations. Bold *p*-values denote statistical significance.

The mid-hip joint center velocities were higher for ascent than decent at perturbation onset ($p < 0.001$; $F_{1,132} = 1090.38$). In addition, ascending perturbations had a smaller (less negative) peak downward mid-hip joint center velocity than descending perturbations ($p < 0.001$; $F_{1,133}$ =

280.17) (Figure 4.1.4). The mid-hip joint center velocity did not significantly change with perturbation number at perturbation onset (p = 0.437; $F_{5,132}$ = 0.99), but the peak downward velocity was slightly reduced (less negative) at the last perturbation than the first (p = 0.032; $F_{5,133}$ = 2.53) (Appendix C.4.1). The mean (standard deviation) mid-hip joint center velocity for ascending and descending climbers was 0.709 (0.180) m/s and -0.015 (0.153) m/s at perturbation onset, respectively. The mean (standard deviation) minimum mid-hip joint center velocity (i.e. peak downward velocity) was -0.869 (0.259) m/s and -1.504 (0.351) m/s for ascending and descend perturbations, respectively.

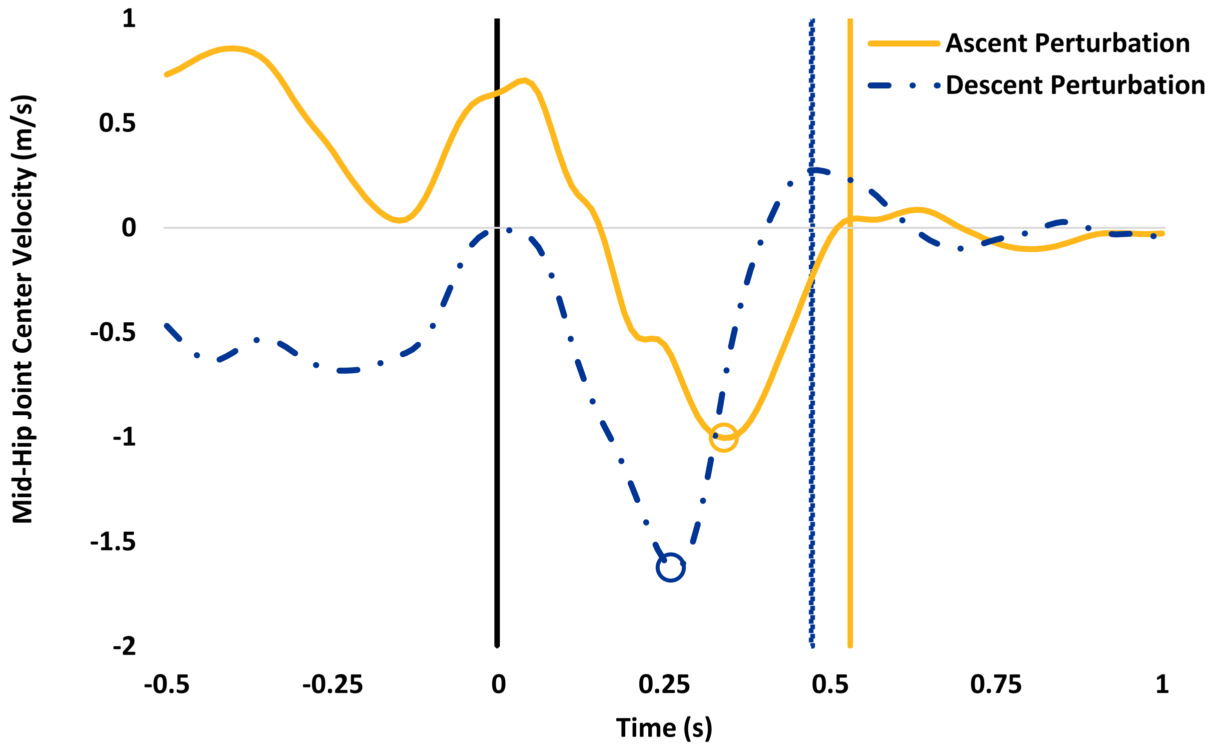


Figure 4.1.4: Mid-hip joint center velocity. Representative velocity of a climber's vertical mid-hip joint center from time of perturbation onset (vertical black line, time = 0) during an ascending (solid yellow line) and descending (dotted blue line) perturbation. The vertical lines following perturbation onset indicate the time of end of fall for ascending (solid yellow) and descending (dotted blue) perturbations.

Gender and the interaction between gender and perturbation order but not glove condition were determined to affect harness force. Harness force did not significantly vary across glove condition during ascent or descent (Table 4.1.2) (Appendix C.4.2). Thus, Hypothesis 4.1.2 was not confirmed. Mean normalized harness force for bare hands, high friction gloves, and low friction gloves was 0.171 (0.154), 0.178 (0.174), and 0.194 (0.184) during ascent and 0.393 (0.261), 0.369 (0.302), and 0.453 (0.302) during descent, respectively. Females had significantly higher normalized harness forces than males during ascent and descent (Table 4.1.2), confirming Hypothesis 4.1.3. Specifically, normalized harness forces were 0.130 (0.137) and 0.257 (0.185) for males and females on ascent and 0.336 (0.237) and 0.501 (0.325) for males and females on descent, respectively. Perturbation order did not influence the overall harness forces for either ascent or descent, thus not confirming Hypothesis 4.1.4 (Table 4.1.2). However, the gender x perturbation number interaction was significant during ascending perturbations (Table 4.1.2). Females had a greater harness force on their second perturbation during ascent compared to male participants (Figure 4.1.5.a). The gender x perturbation number interaction during descent was not significant (p = 0.087, Figure 4.1.5.b). The gender x glove condition and perturbation number x glove condition interactions were not significant for either ascent or descent (Table 4.1.2). In the analysis to assess anticipation, climbing cycle time was not significant across perturbation number for both ascending (p = 0.807; $F_{5,43}$ = 0.46) and descending (p = 0.119; $F_{5,45}$ = 1.87) climbing directions (Appendix C.4.3).

Table 4.1.2: Statistical outcomes from the generalized linear model. The *p*-value and the chi-squared (chi-Sq) for each predictor variable (gender, perturbation number, glove condition) and interactions on normalized harness force (dependent variable) after an ascending (shaded) and descending (non-shaded) perturbation.

	Gender	Perturbation Number	Glove Condition	Gender x Perturbation Number	Gender x Glove Condition	Perturbation Number x Glove Condition
***p*-value**	< 0.001	0.484	0.461	0.020*	0.258	0.135
chi-Sq.	13.254	4.472	1.549	13.391	2.708	14.913
***p*-value**	0.018*	0.065	0.447	0.087	0.140	0.190
chi-Sq.	5.624	10.389	1.610	9.608	3.935	13.636

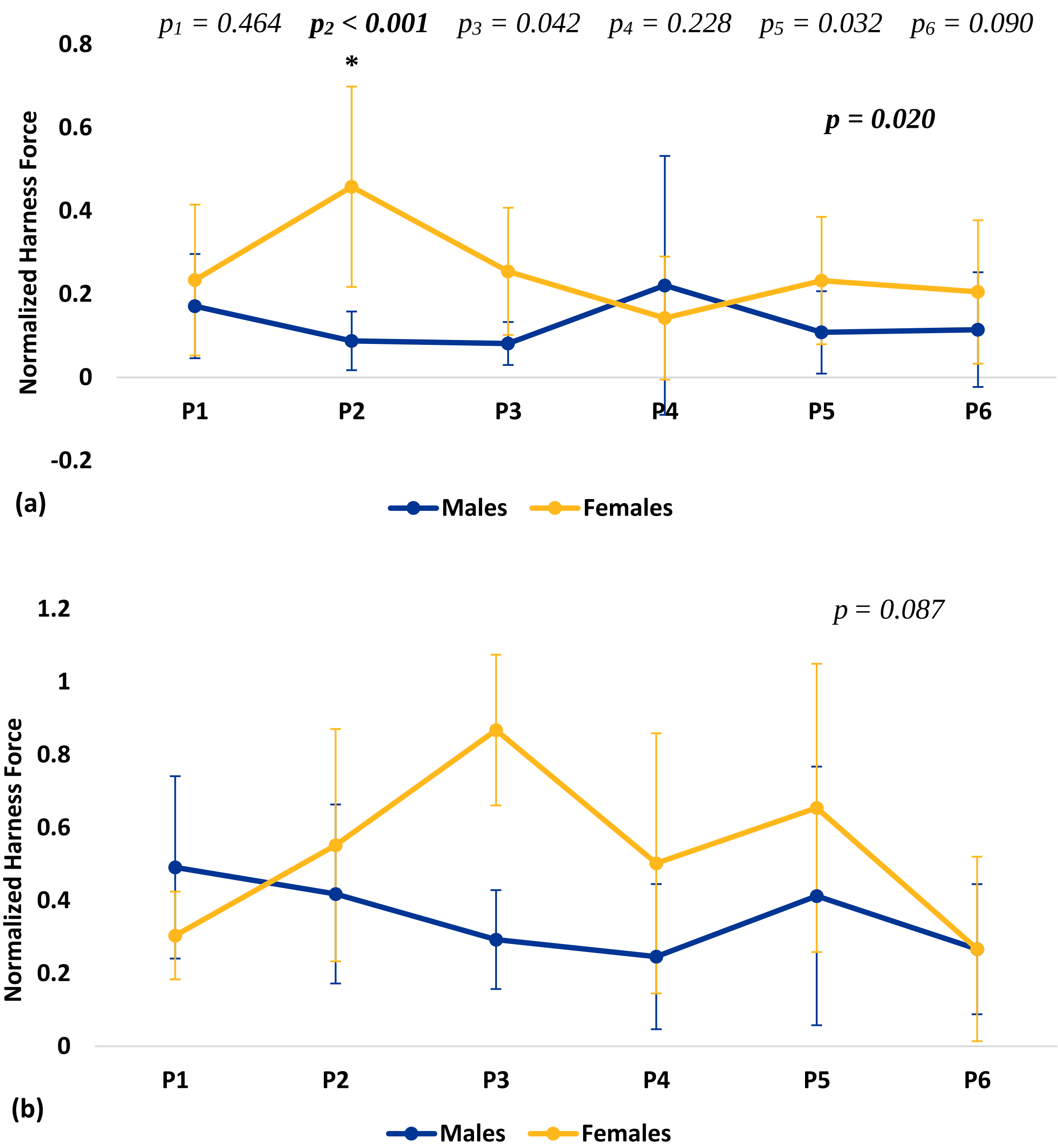


Figure 4.1.5: Harness force by perturbation number. Mean normalized harness force for males (blue lines and blue markers) and females (yellow lines and yellow markers) for perturbations one (P1) through six (P6) during ascent (a) and descent (b). Error bars denote standard deviations. Bold *p*-values denote statistical significance.

4.1.5 Discussion

This study revealed that fall severity (measured via harness force) was greater during ladder descent than ladder ascent, greater for female participants, and that the adaptation process was different for female participants than male participants. Specifically, fall severity initially increased for female participants after one exposure during ascent and then decreased. This finding indicates that female participants who have been exposed to some but not many ladder perturbation may be at increased risk of falling. Interestingly, gloves did not have any impact on fall severity suggesting that this is not a particularly effective intervention for preventing ladder fall events. Climbing cycle time did not change across perturbations, suggesting limited anticipation of the perturbation. However, changes in fall severity across perturbations for female participants suggest adaptations of recovery responses were occurring in these participants. Furthermore, outcomes from this study are consistent when only considering the 1st perturbation (Appendix C.4.4).

This study confirms that ladder descent leads to more severe falls than ladder ascent. Given that a previous study defined a harness weight support threshold for falling to be 30% of body weight [142], the high harness forces for descending perturbations (40% of body weight) indicate that relatively severe falls were observed during descent. The average harness forces during ascent (18% of body weight) were well under this 30% threshold, suggesting that fall severity during ascent was relatively mild. This study suggests the reason that more descending falls have been reported epidemiologically [27] is because ladder descent is a more hazardous task than ladder ascent. Lower fall severity during ascent may be due to the time delay between perturbation onset and when the climber begins to a have downward acceleration. At perturbation onset, the body was confirmed to be moving upward during ascending and downward during descending perturbations (Figure 4.1.4). Thus, the body was already accelerating (as opposed to decelerating) downward at perturbation onset during descending perturbations. This led to a smaller peak downward vertical velocity for ascent, indicating a less severe fall for ascending perturbations than descending [120, 144, 145]. Therefore, the momentum of the body after a perturbation during ladder descent may be too large to recover without assistance from the harness during ladder descent. Increased risk during ladder descent may explain why another study found that participants descended a ladder slower than when ascending a ladder [73]. Also, the act of placing the feet further from the head may reduce the visual information that is available to guide foot placement during descent. Regardless of the mechanism, this study suggests that targeting interventions such as fall arrest systems (e.g. climbing harness with a safety locking sleeve) [67] to ladder descent may be effective at preventing ladder fall injuries.

Glove condition did not affect fall severity. Although previous research indicated that increased force from high friction gloves would reduce ladder fall severity [85, 86], this study did not confirm this effect. One explanation is that the safety harness supported enough of the body weight such that the hand forces did not become great enough to force a decoupling of the hand from the rung. Another explanation is that hand force may not be a limiting factor in fall recovery. Previous research has found that even in low friction handholds, participants were capable of generating forces between 73% and 88% of their body weight for each hand [87]. Additional research that allows the climber to fall a greater distance before engaging the harness may lead to hand-rung decoupling where gloves play a more important role. Overall, this study suggests that increased force from high friction gloves does not translate to reducing fall severity at least during the portion of a fall leading up to the time of harness support.

Females had greater difficulty recovering from a ladder fall than males. Interestingly, fall severity initially increased for females during ascent whereas fall severity for males did not change with continuing perturbations (Figure 4.1.5.a). This result is in contrast to many fall-related perturbation studies, where fall outcome was found to decrease with continuing perturbations [139, 147]. A key difference in this study as opposed to other fall-related studies is that a misstep from a ladder may be a more novel experience than a perturbation experienced during gait. Most individuals have experienced a slip or trip during walking with daily-living, resulting in some form of preset response from the central nervous system [139] whereas a ladder misstep may be a completely new experience. Therefore, a different motor adaptation process may be used to develop effective responses to ladder perturbations. Previous research studies on motor skill development have divided the motor learning process into three phases: exploration, discovery and stabilization, and exploitation [148]. A solution is discovered after an individual has explored many degrees of freedom to find movements most relevant to achieve the desired outcome [148]. This exploration leads to unpredictable outcomes which can be worse than the outcome during the first attempt [149]. Females may have utilized the exploration phase of decision making more than males, resulting in an increase in their fall severity before a decrease. Importantly, females decreased their fall severity after the second perturbation suggesting that they identified a successful recovery response or abandoned exploration and returned to their initial response. Gender differences such as upper body strength [33] and anthropometry [136] may explain why this effect was only seen in females and not males. For example, reduced strength and stature in female participants may have forced them to fine-tune their strategy as opposed to relying on their strength and height. Male participants were taller than females on average ($p < 0.001$) which may have allowed male participants to reach higher for rungs or extend lower to reestablish foot placement onto the rungs after a misstep (Appendix C.4.5).

This research provides important information regarding fall severity factors during ladder climbing that may provide a foundation for future research that investigates interventions and further explores the mechanisms for the observed gender effects. For example, future research may aim to develop interventions that focus on reducing the severity of ladder falls during descent. Also, research that controls for strength and anthropometry may help determine if the gender effects are due to strength and anthropometry differences or due to some other difference. Lastly, training programs that allow female ladder climbers to experience ladder perturbations and go through the exploratory motor learning phase in a safe and controlled environment may lead to safer responses to actual ladder perturbations. Previous research has demonstrated that a perturbation in training can be translated across contexts [150] and from a laboratory environment to a real living environment [151].

This study has a few limitations that should be acknowledged. First, this study only considered a fixed vertical ladder and the results of the study may not be generalizable to all other ladder designs (extension, A-frame, etc.). In addition, this study did not simulate a work task to be performed between ascent and descent. Climbers may be less alert or more fatigued during descent due to a work task that might be performed between ladder ascent and descent. Thus, the effects of climbing direction that were observed in this study may actually be underestimated compared with real work circumstances. Also, the perturbation mechanism, which was intended to mimic the timing of foot decoupling during ladder slips, may not have been representative of all types of ladder slips or missteps since the rung broke away from the ladder. Thus, additional research may be needed to determine if the findings of this study are similar when other types of ladders and perturbation types are utilized. Lastly, a harness system was used to protect participants, which may have interfered with part of the recovery process. However, there was not an increase in harness force with continuing perturbations, indicating that participants were not increasing their reliance on the harness. Yet, additional research that allows participants to fall further before engaging the harness may reveal aspects of recovery that were not considered in this study.

In conclusion, this study identified important climbing and individual factors associated with ladder fall severity. Specifically, descending from ladders was associated with greater fall severity, which explains previous research that found higher prevalence of falls during descent from equipment. Fall protection should be prioritized on ladder descent to maximize fall prevention efforts. Gloves were not found to be a factor that influenced ladder fall severity during the initial fall phase, suggesting that interventions involving gloves may be of limited effectiveness. Females were found to have increased fall severity. The gender difference was particularly pronounced during the 2nd perturbation while ascending the ladder, but this difference disappeared after experiencing several perturbations. This finding suggests that training programs that improve their post-perturbation response may be particularly effective for female climbers.

4.2 Effects of Upper Body Strength, Hand Placement and Foot Placement on Ladder Fall Severity

4.2.1 Abstract

A plurality of fatal falls to lower levels involve ladders. After a slip/misstep on a ladder, climbers use their upper and lower limbs to reestablish contact with the ladder. This study investigates the impact of upper body strength, hand placement and foot placement on fall severity after a ladder climbing perturbation. Participants performed upper body strength tests (breakaway and grip strength) and climbed a vertical, fixed ladder while a misstep perturbation was applied to the foot. After the perturbation, three hand placement and two foot placement responses were generally observed. Common hand placement responses included the hand moving two rungs, one rung, or did not move to a different rung. Foot placement responses included at least one foot or no feet reestablished contact with the ladder rung(s). Fall severity was quantified by the peak harness force observed after the perturbation. Increased strength, reestablishing feet on the ladder, and ascending (compared with descending) the ladder was associated with a reduction in fall severity. An interaction effect indicated that the impact of hand placement was altered by climbing direction. Moving the hand one rung during ascent and moving the hand two rungs during descent was associated with an increased fall severity. Failing to maintain hand-rung contact typically led to higher fall severity. Upper body strength assessed using a portable grip dynamometer was sufficient to predict fall severity. This study confirms the multifactor role of the upper body strength, hand placement and foot placement in preventing falls from ladders. Furthermore, a portable dynamometer shows potential to screen for high-risk individuals. Results of this investigation may guide targeted interventions to prevent falls from ladders.

4.2.2 Introduction

The majority of fatal fall injuries are from a height [24]. Fatal fall injuries have increased 26% from 2011 to 2016 with the plurality of these injuries occurring from a ladder [25]. Understanding potential strategies to prevent falls from a ladder is important to reduce fatal falls and disabling injuries.

Upper body strength is considered to be an important factor that contributes to arresting a fall from a ladder. Not all individuals are capable of generating enough force to support their full body weight with one hand [85, 87]. Also, prediction models of a person's ability to stop a downward fall suggest that individuals with higher upper body strength are more likely to recover [83]. However, the relevance of upper body strength in preventing ladder falls has not been demonstrated in actual ladder climbing perturbation studies.

Other factors that influence recovery or fall severity include the response of the upper and lower body to a perturbation. The placement of the hands may be important to recovery since the hands stabilize the climber during ladder climbing by pulling the climber towards the ladder [76, 83]. Furthermore, the hands contribute to balance recovery by applying vertical forces after a perturbation during climbing [85, 87]. Preliminary observations of responses to a perturbation during ladder climbing have revealed multiple hand placement responses occur to re-grasp a handhold [152]. Hand placement response may affect recovery during a fall from a ladder, similar to the impact of the trailing leg response on recovery during gait slip perturbations [153, 154]. Characterizing hand placement responses and their effect on recovery from a climbing perturbation could guide interventions for preventing falls from ladders.

Reestablishing the feet may be another important factor to arrest a fall after a perturbation during ladder climbing. The lower body supports the majority of the climber's weight during ladder climbing [76]. Also, the foot placement on the rung affects the climber's risk of slipping [80]. The lower-limb muscles actively respond to a climbing perturbation [82], indicating that replacing the feet on the ladder may be part of the active balance recovery response.

While these factors have been suggested to influence fall severity in the literature, there currently exists little evidence demonstrating their impact on fall risk during ladder climbing. Therefore, the purpose of this study was to determine the effect of upper body strength, hand placement and foot placement on fall severity after a ladder climbing perturbation by answering the following question:

Research Question: Is ladder fall severity affected by upper body strength, hand placement and foot placement?

In addition, this study quantified differences in fall severity predictions between upper body strength measurements using a laboratory equipment setup [83, 85, 87] and a portable grip dynamometer. A dynamometer grip strength test is considered more practical since it can screen individuals *on site* to identify the highest risk individuals.

4.2.3 Methods

This study consisted of an upper body strength testing session [84] and exposure to perturbations during a ladder climbing testing session [127], performed on separate days.

4.2.3.1 Participants

Thirty-five participants between the ages of 18 and 35 years participated. Seven participants were excluded from the data analysis due to equipment malfunction or participant withdrawal (i.e. excluding participants with partial or no complete data) (Appendix C.3.1). This study analyzed data on 28 participants including 17 males (23.8±4.6 yrs., 81.8±8.7 kg, 1.8±0.1 m) and 11 females (25.2±6.4 yrs., 62.7±6.2 kg, 1.7±0.1 m). Approval was obtained by the Institutional Review Board and testing was performed at the University of Wisconsin-Milwaukee. Informed consent was obtained prior to each testing session. Those with musculoskeletal disorders, previous shoulder dislocations, osteoporosis/osteoarthritis, neurological/cognitive disorders, balance disorders, or pregnancy were excluded. This study represents a secondary analysis of a ladder climbing fall risk experiment [84, 127] to assess a potential link between individual strength and recovery from a perturbation during ladder climbing.

4.2.3.2 Testing session 1: Upper body strength

During the first session, breakaway strength (peak force applied to a rising rung prior to the hand decoupling) and grip strength on a dynamometer were measured. The breakaway strength test was performed using a custom-laboratory-based apparatus involving an aluminum cylindrical rung (diameter: 32 mm) in-line with a motorized pulley system and load cell [84, 85] (Appendix C.3.6). The load cell measured the force applied to the rung by the hand (1 kHz) while the motor pulled the rung out of the hand (i.e. breakaway) [84]. Grip strength was measured utilizing a commercially available dynamometer (Jamar® 5030J1, Patterson Medical, Warrenville, IL). Participants stood upright with their shoulder neutral and elbow flexed at 90º and exerted their maximum grip force between the two parallel bars on the dynamometer for five seconds, consistent with the duration for the breakaway strength test. For each strength test, two repeated trials were performed for each hand (left and right) and each of three glove conditions (bare hands, cotton gloves, latex-coated gloves) (Appendix C.3.5). The maximum force recorded for each trial was averaged across all twelve trials to determine a participant's breakaway and grip strength. The impact of glove condition was previously reported [84, 85] and is not considered in this study. All strength measurements were normalized to body weight.

4.2.3.3 Testing session 2: Response to a ladder climbing perturbation

Participants wore tight-fitting athletic clothing, standard work shoes with a raised heel, shin guards, a safety harness, and 47 reflective markers (Appendix C.3.2, Appendix C.3.3). The harness was attached to a load cell (1 kHz) to measure the weight supported by the harness. Relevant marker locations for this study included the anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), 3rd metacarpal head, 1st and 5th metatarsal heads, and middle toe (i.e. middle and most anterior point on the superior surface of the shoe). Reflective markers were recorded with 13 motion capture cameras (100 Hz) (Motion Analysis Raptor Corp., Santa Rosa, CA.) (Appendix C.3.4).

Participants were instructed to climb a 12-foot, vertical ladder at a comfortable but urgent pace to simulate climbing speed of a regular-to-busy work day. The ladder was custom-built in compliance with the U.S. Occupational Safety and Health Administration (OSHA) standards. The rung diameter was 32 mm, consistent with the rung dimensions/material used in testing session 1, and rungs were spaced 305 mm apart [92] (Figure 4.1.1). Five reflective markers were placed on the ladder to determine the ladder's position relative to the climber. Participants experienced a total of six ladder climbing perturbations, in each climbing direction (ascent, descent) and for the three glove conditions. Participants practiced climbing the ladder until they were comfortable in each climbing condition. Order of climbing perturbation was randomized. Prior to each climbing perturbation, climbers performed regular climbs three to six times (with the exact number randomly chosen and unknown to the participants) to reduce anticipation of a perturbation. The perturbations resembled a ladder misstep and were generated by decoupling the fourth rung from the ladder rails shortly after foot contact. This time point was consistent with the time when a person's foot is most likely to slip off of a ladder rung [82, 127].

Ladder fall severity was quantified from the load supported by the harness. The peak harness force (referred to as harness force hereafter) was found between perturbation onset and end of the perturbation response and normalized to body weight (Figure 4.1.2) [127]. A higher harness force was interpreted as a greater likelihood of the perturbation resulting in a fall. Harness force data was filtered using a zero-lag, 4^{th}order low-pass Butterworth filter with a cut-off frequency of 36 Hz [146]. Nine trials were removed due to incongruence between the end of perturbation response identified by an algorithm [127] and visual inspection.

Three common hand placement responses and three foot placement responses were observed. Most participants established two hands in contact with the ladder rung(s) by the end of the perturbation, but the placement of hands varied across trials (Figure 4.2.1). The three most frequent hand placement responses were: HM2 – hand moved two rungs (Figure 4.2.1.a, consistent with unperturbed climbing), HM1 – hand moved one rung (Figure 4.2.1.b), HM0 – the hand did not move to a different rung (Figure 4.2.1.c). The movement direction was consistent with the climbing direction (i.e. HM2 would signify the hand moved two rungs up for ascent or two rungs down for descent). The two foot placement responses were: reestablished – one or both feet reestablished contact with the ladder rung(s) (Figure 4.2.1.d), and not reestablished – neither foot reestablished contact with the ladder rungs (Figure 4.2.1.e). In nine of the trials, other hand placement strategies were observed including the hands decoupling from the rung that was grasped

(4 trials, decoupled), the moving hand failing to reestablish hand contact until after the end of perturbation response (i.e. peak harness force) (3 trials, hand not reestablished), or the hand moved three rungs (2 trials, HM3). Normalized harness force data of these trials were reported but not included in the statistical analysis due to their rarity.

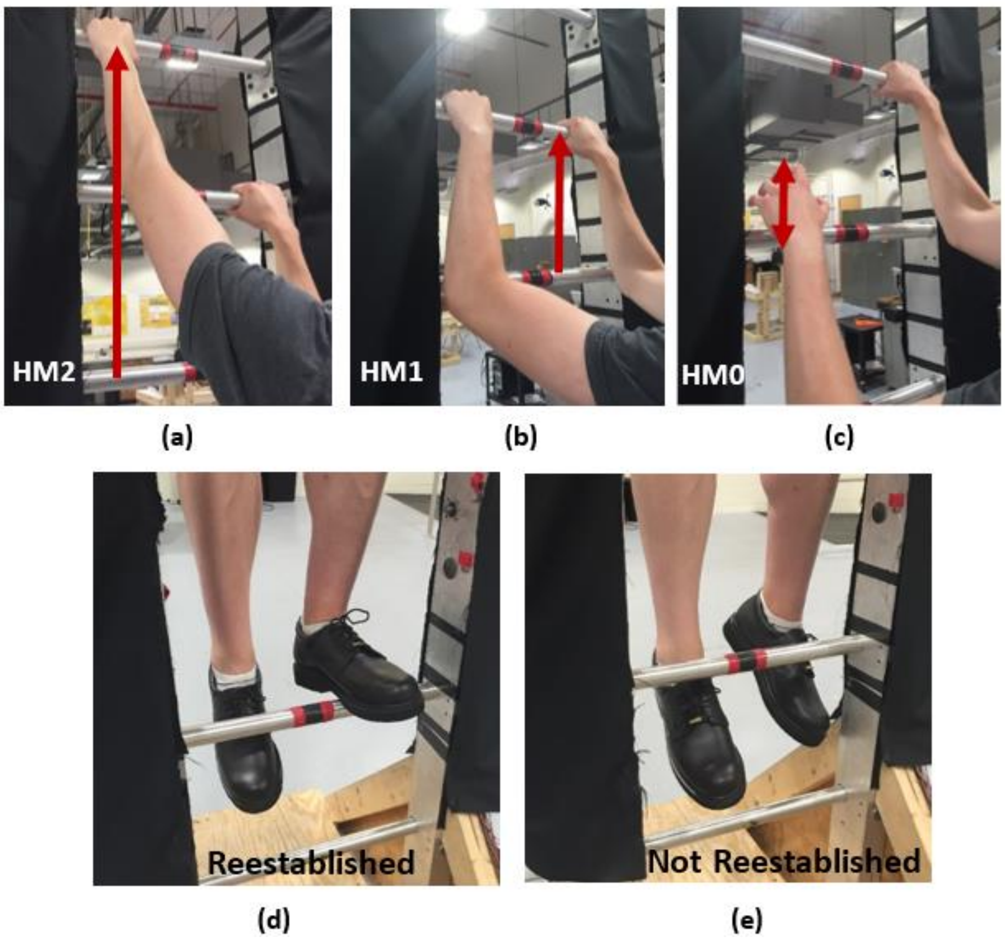


Figure 4.2.1: Hand placement responses. The most common hand placement responses included: hand moved two rungs (a), hand moved one rung (b), and hand ended at starting position (c). Foot placement responses included at least one foot reestablished contact with the ladder rung (d) and no foot reestablished contact with the ladder rung (e).

Hand placement response was found for the hand that was either moving or about to move during perturbation. Hand movement onset and offset were identified when the vertical velocity of the 3rd metacarpal marker exceeded and fell, respectively, below 10% of the metacarpal's peak velocity from the hand's prior movement [82]. Foot contact was identified if the vertical deceleration of the foot (midpoint between 1st and 5th metatarsal and middle toe markers) exceeded 0.5 m/s^2 when the foot was within a 40 mm distance of the rung's top surface in the vertical and horizontal direction. The foot was only considered to have reestablished contact if the foot maintained contact (i.e. did not slip off) until the end of the perturbation, which was confirmed visually. Acceleration data was used to classify foot-rung contact because the foot hit the rung at various velocities that could not be correctly categorized by a velocity threshold. Position data was filtered using a zero-lag, 2nd order Butterworth low-pass filter with a cut-off frequency of 10 Hz [82] and differentiated to calculate velocity and acceleration.

4.2.3.4 Statistical analysis

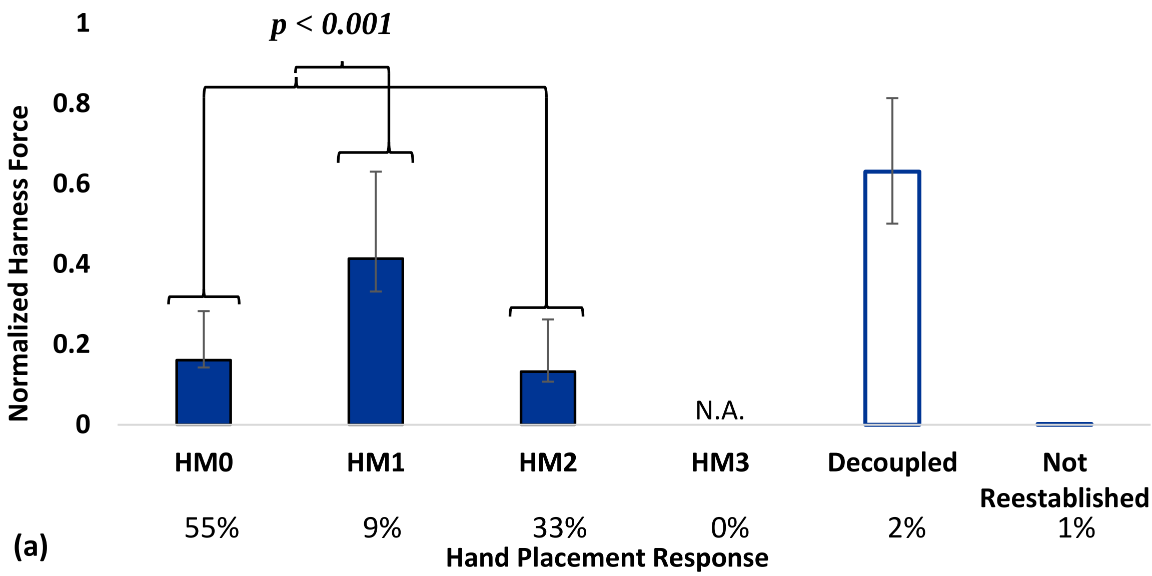
Repeated-measures ANOVAs were performed to identify the effect of upper body strength, hand placement and foot placement on harness force (proxy of fall severity). The models included participant number (random), climbing direction, hand placement, foot placement, upper body strength (breakaway strength for the first model and grip strength for the second model) and all first order interactions (e.g. climbing direction x hand placement). A significance level of 0.05 was used. When interactions involving climbing direction were found to be significant, post-hoc ANOVA models were performed for both climbing directions. Tukey HSD post-hoc analyses were performed on variables with more than two levels (i.e. hand placement). A square root transformation was performed on normalized harness force to achieve normal residuals. Spearman's correlations were computed to study the relationship of breakaway and grip strength on harness force. In addition, the adjusted R^2 values of the ANOVA models (with all included variables and first order interactions) were reported as a measure of each model's prediction quality (Table 4.2.1). Statistical software (JMP®, Version 14. SAS Institute Inc., Cary, NC.) was used to perform the analyses.

Table 4.2.1: Statistical analyses. The dependent and predictor variables in each statistical analysis. Additional test details are noted (random variables). ANOVAs 1 & 2 are the primary analyses to investigate the research question. Spearman's correlations are secondary analyses.

Analysis	Dependent variable	Predictor variable	Other variable
ANOVA 1	Harness force	Climbing direction, hand placement, foot placement, breakaway strength, interactions	Participant number (random)
ANOVA 2	Harness force	Climbing direction, hand placement, foot placement, grip strength, interactions	Participant number (random)
Spearman's correlation	Harness force	Breakaway strength, grip strength	NA

4.2.4 Results

The mean (standard deviation) normalized harness force was 0.28 (0.25) after a climbing perturbation (corresponding to 28% body weight). The mean (standard deviation) normalized breakaway strength and grip strength was 0.74 (0.19) and 0.51 (0.10), respectively. The prevalence of hand and foot placement responses varied across ascending and descending perturbations (Figure 4.2.2, Figure 4.2.3).



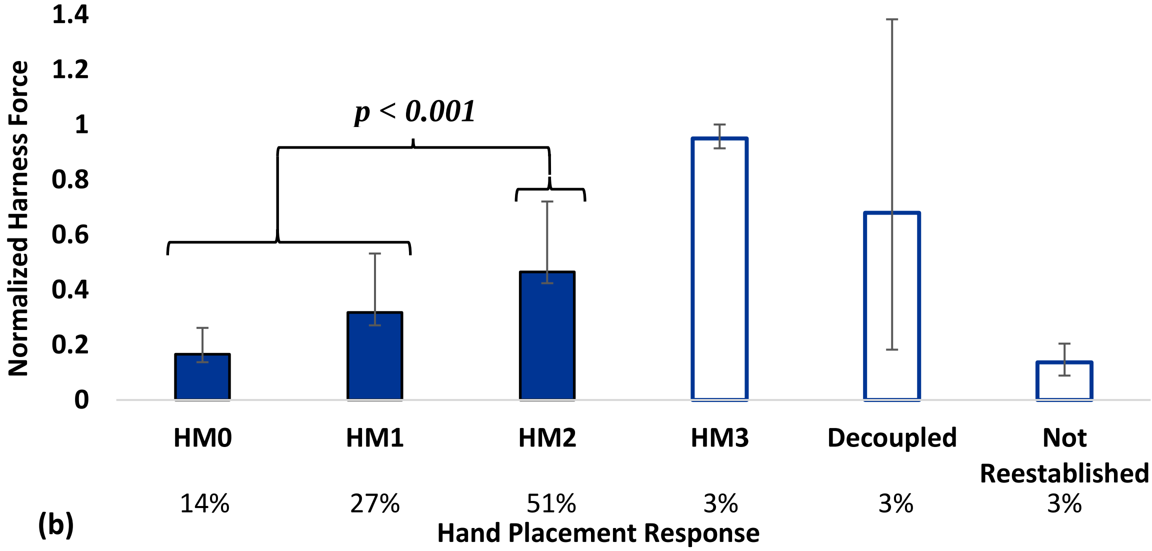


Figure 4.2.2: Harness force by hand placement response. Mean normalized harness force across hand placement responses during ascending (a) and descending (b) perturbations. Occurrence (percentage) of each hand placement response is displayed on the horizontal axis below each hand placement response label. Statistical analysis was not performed for trials where the hand moved three rungs (HM3), decoupled from the rung (decoupled), or left the rung, but did not reestablish hand contact prior to end of perturbation response (hand not reestablished) (white bars). N.A. indicates that no data was recorded for that condition. Standard deviation of normalized harness force is represented by the positive error bars and standard error of normalized harness force is represented by the negative error bars. Bold *p*-values denote statistical significance.

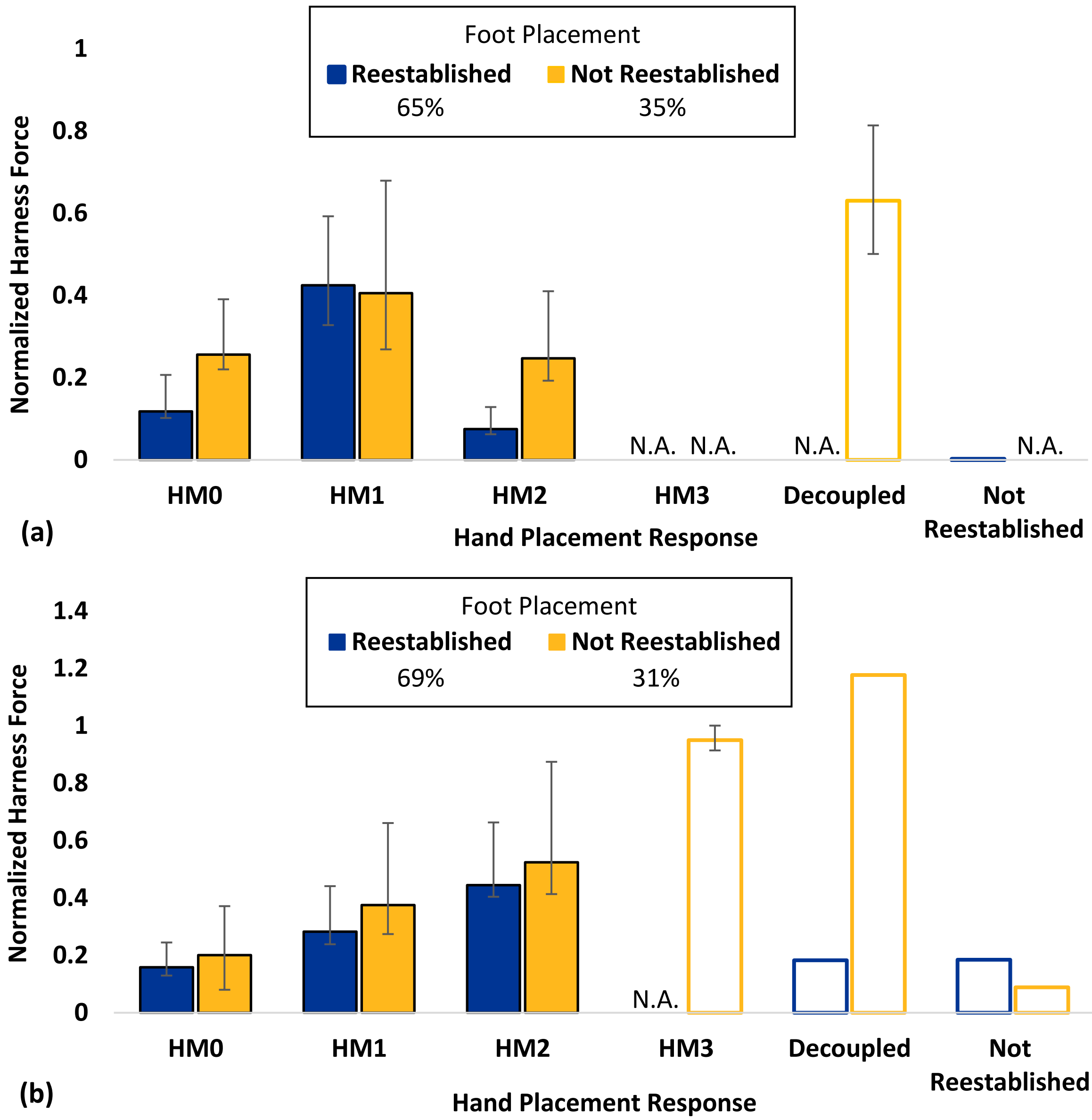


Figure 4.2.3: Harness force by hand and foot placement response. Mean normalized harness force for hand and foot placement combinations after ascending (a) and descending (b) perturbations. Certain hand placement outcomes were not included in the statistical analyses including HM3, decoupled or hand not reestablished (outlined bars). Data elements, where the foot reestablished contact, are represented by the blue bars and data elements, where the foot did not reestablish contact, are represented by the yellow bars. Occurrence (percentage) of each foot placement response is displayed under the legend below each foot placement response label. N.A. indicates that no data was recorded for that condition. Standard deviation of normalized harness force is represented by the positive error bars and standard error of normalized harness force is represented by the negative error bars.

In both repeated measures ANOVA models (i.e. breakaway strength and grip strength), climbing direction, hand placement, foot placement, upper body strength, and climbing direction x hand placement affected normalized harness force. No other interaction effects in either model were statistically significant (Table 4.2.2).

Table 4.2.2: Statistical outcomes from ANOVA models. Models with breakaway strength and grip strength (degrees of freedom, *p*-value, *F*-value). Bolded *p*-values are statistically significant at 5% level.

		Breakaway Strength		**Grip Strength**	
	df1, df2	*p-value*	*F-value*	*p-value*	*F-value*
Climbing Direction	1, 141	**0.019**	5.69	**0.016**	5.94
Hand Placement	2, 141	**0.002**	6.52	**0.003**	5.96
Foot Placement	1, 141	**0.019**	5.66	**0.013**	6.29
Upper Body Strength	1, 141	**0.020**	6.05	**<0.001**	16.50
Climbing Direction x Hand Placement	2, 141	**<0.001**	13.93	**<0.001**	17.29
Climbing Direction x Foot Placement	1, 135	0.112	2.56	0.086	2.99
Climbing Direction x Upper Body Strength	1, 135	0.615	0.25	0.800	0.07
Hand Placement x Foot Placement	2, 135	0.941	0.06	0.729	0.32
Hand Placement x Upper Body Strength	2, 135	0.718	0.33	0.724	0.32
Foot Placement x Upper Body Strength	1, 135	0.473	0.52	0.076	3.20

Since the climbing direction x hand placement interaction was significant, a post-hoc ANOVA model was performed to determine the effect of hand placement on ascent and descent. During ascent, moving the hand one rung up (HM1) was associated with greater normalized harness forces than moving the hand two rungs up (HM2) or ending at the starting rung (HM0) ($p < 0.001$; $F_{2,76} = 8.39$) (Figure 4.2.2.a). During descent, moving the hand two rungs down (HM2) was associated with a greater normalized harness forces than hand responses where the hand moved only one rung down (HM1) or ended at the starting rung (HM0) ($p < 0.001$; $F_{2,68} = 9.87$) (Figure 4.2.2.b). Reestablishing at least one foot back onto the rung (normalized harness force mean: 0.24; standard deviation: 0.21) was associated with lower harness forces than not reestablishing a foot (normalized harness force mean: 0.34; standard deviation: 0.25) (Figure 4.2.3). Hand placement of decoupled and HM3 resulted in higher normalized harness forces than other hand placement responses with the exception of one case in which the person's hand decoupled while reestablishing their feet during descent (no statistics performed, Figure 4.2.3.b). Interestingly, participants who experienced a decoupling between the hand and the rung (decoupled) had low-to-moderate upper body strength (53% to 63% of body weight) (no statistics performed). Cases in which participants voluntarily released a rung and did not grasp another rung (hand not reestablished) by the end of the trial had generally lower harness forces than the other hand placements (Figure 4.2.2).

Normalized harness force was negatively correlated (low-to-moderate) with breakaway strength ($p = 0.001$; $\rho = -0.264$) (Figure 4.2.4.a) and grip strength ($p < 0.001$; $\rho = -0.329$) (Figure 4.2.4.b). When comparing the ANOVA models with breakaway strength vs. grip strength, the models yielded similar predictions of harness force, producing the same adjusted R^2 value ($R^2 = 0.69$). This indicates grip strength to be as good of a predictor of harness force as breakaway strength.

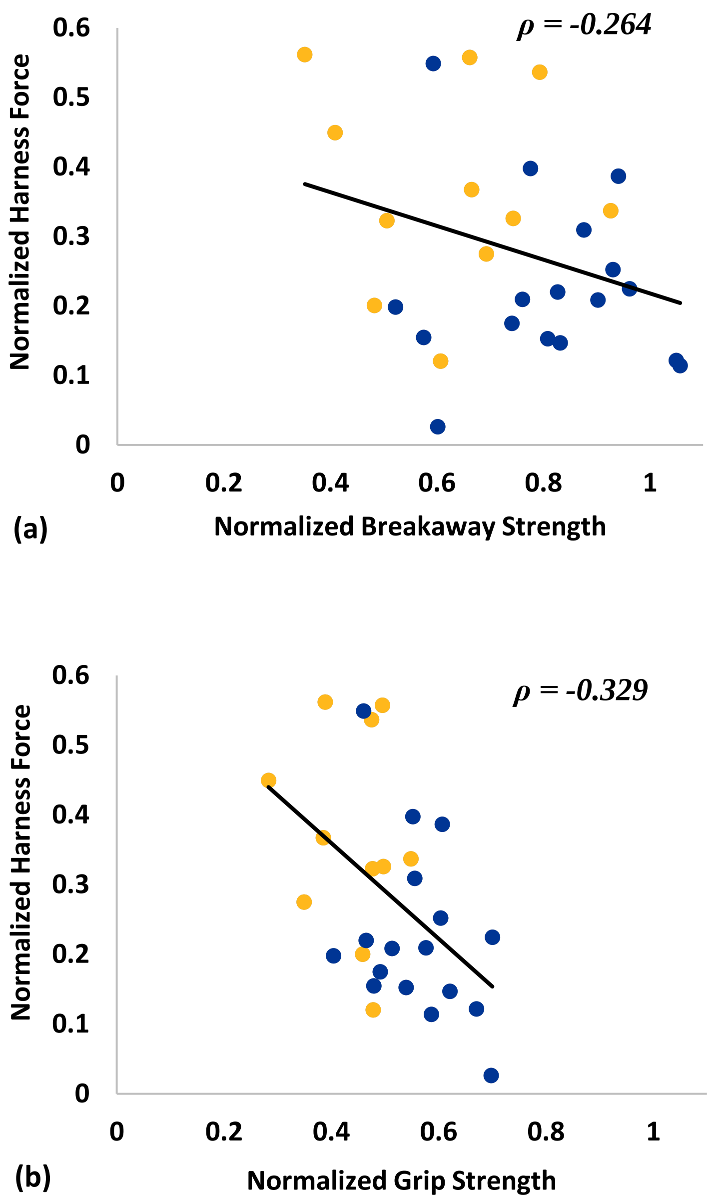


Figure 4.2.4: Relationship between harness force and upper body strength. Mean normalized harness force with normalized breakaway strength (a) and grip strength (b). Each dot represents a person's mean normalized harness force across all six perturbations. Male participants are represented by the blue dots and female participants are represented by the yellow dots. The solid line represents the best linear fit. Spearman's correlations (ρ) are displayed on each graph. Bold correlations denote statistical significance.

4.2.5 Discussion

Upper body strength was negatively correlated with fall severity (measured via harness force) after a simulated misstep. Hand placement, foot placement, and climbing direction also contributed to the fall severity. Grip strength was found to be as good of a predictor of fall severity as breakaway strength.

An increase in upper body strength was associated with lower fall severity. Breakaway strength and grip strength were both significant predictors of ladder fall severity. Both active (finger flexion) and passive (frictional) forces contribute to breakaway strength, whereas only the active (finger flexion) forces contribute to grip strength (see Appendix C.4.6 for variation between strength measures) [85, 88, 155]. The passive forces due to friction have been previously thought to be important to ladder recovery, which would suggest that breakaway strength would better predict fall risk [85, 87, 88, 155]. However, the results of this study do not support this view. We should note, however, that the harness system used in this study typically caught participants before their hands fully decoupled from the rung and that breakaway strength might become more relevant in the absence of the harness system [127]. In addition, participants gripped the ladder rungs (i.e. horizontal orientated handhold) in this experiment and passive forces are likely more important when grasping rails (i.e. vertically orientated handholds). Therefore, this finding should be further monitored. Nevertheless, the results of this study are encouraging since grip strength tests are easier and less expensive to administer than breakaway strength. Low-to-moderate strength individuals appear to be at risk of their hand decoupling from the rung after a ladder climbing perturbation. Therefore, simple grip strength assessment may be used to identify and target interventions to individuals at greater ladder fall risk.

The role of hand placement on fall severity may be due to a combination of factors. The hand placement after a climbing perturbation may be the net effect of the hand's position at perturbation onset, the active response of the upper body after perturbation onset, and the dynamics of the body during falling. Differences in fall severity by hand placement may be partially attributed to the amount of force a hand can generate in different arm postures [84] and the time available to generate force. The upper body's capacity to generate pulling force increases with a higher hand placement relative to the body [84]. During ascending climbs, having a mid-reach arm posture (HM1) after a perturbation may have limited the amount of upper body pulling force that could be generated compared to HM2. One explanation for why this same effect was not observed in HM0, is that the hand may spend more time in contact with the rung for this response (Appendix C.4.7) [156]. Thus, HM1 may be a response that neither benefits from the strength advantage of a higher reach nor the large time in contact that may be occurring with HM0. The lower fall severities for HM0 and HM1 during descending climbs, may similarly be linked with having a higher hand position. Once again, this would lead to a higher upper body force generation capacity, compared to HM2. While no statistical analysis was performed, the higher harness forces that were generally associated with the decoupling hand placement responses (decoupled) suggests that reestablishing the hands back onto the ladder rungs is a critical component of arresting a ladder fall.

Similar to hand placement, foot placement after a climbing perturbation may be the net effect of the foot's position at perturbation onset, the active response of the lower body after perturbation onset, and the dynamics of the body during falling. In some cases, the foot contacted the ladder rung but slipped off (Appendix C.4.8), resulting in not reestablished foot placement. Cases where the perturbed foot maintained foot-rung contact (i.e. reestablished foot placement) were associated with a greater foot angle (toe up from horizontal) at perturbation onset (Appendix

C.4.9). At foot-rung contact after the perturbation, a flatter foot (as oppose to toe down from horizontal) and a more anterior foot position with respect to the ladder rung midpoint were associated with maintained foot-rung contact (Appendix C.4.10) [157]. Furthermore, foot slip outcomes after foot-rung contact where associated with earlier foot-rung contact times (Appendix C.4.11) [158]. Regardless of mechanism leading to reestablished foot placement, this study found, reestablishing at least one foot onto the ladder rung was associated with a lower fall severity. Reestablished foot placement likely reduced fall severity by supporting the climber's body weight consistent with unperturbed climbing [76].

Ascending perturbations (compared to descending) were associated with a lower fall severity. Higher fall severity during descent compared with ascent was previously discussed for this data set in one of our earlier papers [127].

Possible interventions may be informed by the results of this study. First, strength-building or weight loss interventions may be valuable for lower-strength individuals or individuals that have more body weight to support. Climbers may also benefit from leading with their hands during ascending climbs and leading with their feet during descending climbs to promote a more elevated hand position. In addition, interventions that optimize ladder design (e.g. rung spacing, ladder angle) may improve a climber's ability to reestablish foot placement. Intervention that consider the combinations of increased upper body strength, optimal hand placement and reestablished foot placement may lead to a greater likelihood of ladder fall recovery (Appendix C.4.12) [159, 160].

This study has limitations that should be acknowledged. Only a vertical ladder was tested. The interference of the safety harness limits the knowledge of the eventual fall outcome, had the harness not been used. In addition, factors contributing to hand and foot placement responses were not assessed in detail. Future studies should determine the effects of perturbation timing and body dynamics during falling on hand and foot placement responses.

This study demonstrates that the upper body strength of a ladder climber and the hand and foot placement responses after a perturbation influence fall severity. This information may be useful in developing training programs to increase strength or weight loss and promote preferable climbing patterns through climber training or ladder design. These activities may lead to a reduction of fall injuries from ladders.

4.3 Hand-Rung Forces after a Ladder Climbing Perturbation

4.3.1 Abstract

The hands are believed to be important for arresting falls from ladders. Yet, there is a paucity of kinetic data for the hand-handhold interface during recovery from a ladder climbing perturbation. This study quantified the hand-rung forces utilized after ladder climbing perturbations and the factors (upper body strength, fall severity, reestablished foot placement) contributing to hand-rung force. A ladder rung was released under the foot of the participants to simulate a climbing misstep perturbation. Hand-rung forces after the perturbation were quantified from uniaxial load cells connected to two ladder rungs. Average peak hand-rung force magnitudes were found to range between 50% and 75% of the climber's body weight. These magnitudes approached and, in some cases, exceeded individuals' grasping capacity. Hand-rung force was independent of individual upper body strength, but increased with severity of the falling event after an ascending perturbation. Individuals that reestablished foot placement after an ascending perturbation utilized lower hand-rung forces. Therefore, this study suggests hand-rung force to be dependent on circumstances of the falling event (fall severity, reestablished foot placement) as opposed to the climber's capability of producing upper body force. This knowledge highlights the importance of handhold and ladder designs for arresting a falling event, and is critical to inform ladder fall interventions such as designing handholds that resist high forces and permitting steps that enable reestablished foot placement.

4.3.2 Introduction

Ladder falls are a problem globally [31-35, 37, 38]. In the occupational setting, falls from ladders are the leading cause of fatal falls to lower levels [26]. Even non-fatal ladder falls cause severe injuries, resulting in 20 median days away from work [42]. To target interventions that reduce ladder fall injuries, this study will investigate factors that are relevant to arresting a ladder fall.

The hands are critical to ladder climbing. The feet support the majority of body weight (i.e. vertical force), the hands stabilize the climber by pulling the body towards the ladder (i.e. horizontal force) [76, 161]. The hands also play a critical role in arresting a ladder fall and may be the only limb in contact with the ladder after a ladder climbing perturbation (e.g. foot slip or misstep) [82]. In these cases, the hand is required to generate or withstand large forces. Previous studies have measured the maximum force that can be generated across ladder handhold designs before the hand's grasp breaks away from the handhold [84, 85, 87]. Participants in these experiments were in a stationary posture (seated or standing), while holding onto a handhold that was pulled from their grasp. However, the hand forces generated in response to perturbations during ladder climbing are not well understood. In contrast, research on handrail design for stairs has benefited from studies that 1) quantified the forces generated during recovery responses [162-164]; and 2) force capacity between the hand and rung for different handrail designs [165]. Similarly, new knowledge on the hand forces during recovery from a ladder misstep event will add important context to previous studies that measured force capacity across ladder handhold designs for arresting a climbing perturbation.

Hand-rung forces observed after a ladder climbing perturbation may be influenced by an individual's force-generating capacity or by the circumstances of the fall. Individuals with greater upper body strength may leverage their higher capacity to generate greater forces. Alternatively, increased hand-rung force may be generated in response to a more severe falling event. If the latter is true and the generated hand-rung forces approach or exceed individual hand-rung grasping capabilities, the hand would be at risk of decoupling (force required to recover > hand-rung grasping capability). Thus, understanding the factors contributing to hand-rung force will assist in determining if the hand is at risk of decoupling. This study will investigate the relationship of hand-rung force utilized after a ladder climbing perturbation with individual upper body strength and the severity of the falling event.

While both the upper and lower extremities respond to a ladder climbing perturbation [82, 128], the interaction between the upper and lower body is not well understood. Therefore, this study will also investigate the relationship between hand-rung force and reestablished foot placement to better understand the upper and lower body interaction after a ladder climbing perturbation.

The purpose of this study is to quantify hand-rung forces after a ladder climbing perturbation. This study will also determine contributing factors of hand-rung force by testing two competing hypotheses.

Hypothesis 4.3.1: Hand-rung force will be higher for individuals with greater upper body strength.

Hypothesis 4.3.2: Hand-rung force will increase with severity of the falling event.

Lastly, this study will explore the upper and lower body interaction after a climbing perturbation by investigating hand-rung force with reestablished foot placement

4.3.3 Methods

4.3.3.1 Participants

Thirty-five participants completed two testing sessions. The first testing session assessed individual upper body strength [84] and the second testing session assessed the climber's biomechanical response after a ladder climbing perturbation [127, 128]. Technical equipment error prevented assessment of four participants (i.e. no data) (Appendix C.3.1). Therefore, data from 31 participants (25 ± 5 years of age; 74.2 ± 12.1 kg; 1.8 ± 0.1 m) were analyzed in this study. Exclusion criteria consisted of musculoskeletal disorders, previous shoulder dislocations, osteoporosis/osteoarthritis, neurological/cognitive disorders, balance disorders or pregnancy. Approval was obtained by the Institutional Review Board at the University of Wisconsin-Milwaukee. The work presented in this manuscript is an exploratory secondary analysis. Hypothesis driven aims and more in-depth methodological details of this study have been previously reported [84, 127, 128].

4.3.3.2 Testing session 1: Upper body strength

Upper body strength was assessed via a breakaway strength test [85, 87]. With one hand, participants were asked to hold onto a cylindrical (32 mm diameter) rung that was positioned horizontally and raised vertically until the rung broke away from their grasp. Participants were seated securely throughout the approximately, five second rise of the rung [84, 85] (Appendix C.3.6). The peak force generated onto the rung prior to rung breakaway was recorded as the participant's upper body strength (i.e. breakaway strength). Participants completed this task under six conditions: two hands and three glove conditions (wearing no gloves, low friction glove, high friction gloves) (Appendix C.3.5). Conditions were randomized with two trials performed in each condition. Participants were allowed rest as needed. This data set has previously found glove condition to minimally affect ladder fall severity [127] and breakaway strength [84]. Thus, effects of glove condition on hand-rung force is not considered in this study.

4.3.3.3 Testing session 2: Response to a ladder climbing perturbation

Participants were equipped with athletic wear, standard shoes with a raised heel, shin guards and a safety harness. The safety harness was attached to a load cell (collection at 1kHz) to measure the harness reaction force (referred to as the harness force hereafter) and aligned with a fall arrest system [127]. Forty-seven reflective markers were secured to anatomical landmarks [127, 128] (Appendix C.3.2, Appendix C.3.3) and tracked by 13 motion capture cameras (collection at 100 Hz) (Motion Analysis Raptor Corp., Santa Rosa, CA) (Appendix C.3.4).

A vertical, 12-foot ladder was custom-built in compliance with the US Occupational Safety and Health Administration (OSHA) standards. The rungs were identical to the rung used in the previous breakaway strength experiment and spaced 205 mm apart [92]. The 8th and 9th rungs from the bottom of the ladder were equipped with uniaxial load cells (collecting at 2kHz) to measure the applied horizontal (anterior-posterior) and vertical (superior-inferior) forces (Figure 4.3.1.a & b). Horizontal forces in the medial-lateral direction were not measured as previous ladder climbing research has found these forces to be negligible [79, 81]. The 4th rung (from the bottom) could be triggered to release (i.e. perturbation onset) when less than 5% of the participant’s body weight remained on the rung below or above the 4th rung for ascending and descending perturbations, respectively (Figure 4.3.1.c). This simulated a ladder misstep and occurred at a point in time when a climber’s leading foot is most likely to slip [82].

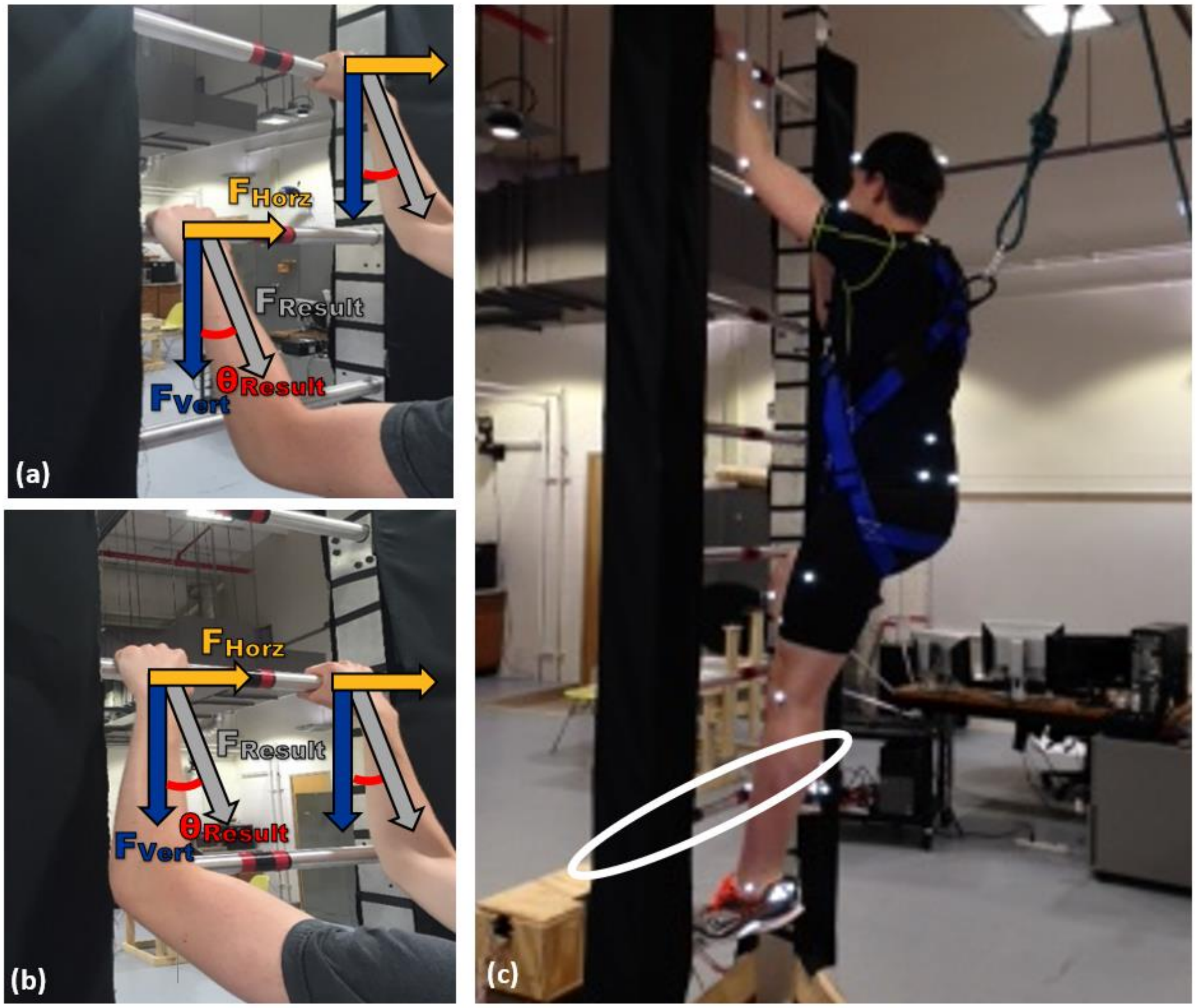


Figure 4.3.1: Schematic of hand-rung force after a ladder climbing perturbation. Applied horizontal (F_{Horz}), vertical (F_{Vert}), and resultant (F_{Result}) force from the hands onto two rungs in a staggered position (a) or one rung in a together position (b). Horizontal forces are in the anterior-posterior direction. A positive resultant force angle (θ_{Result}) is counter-clockwise from vertical. Participant climbing the vertically fixed ladder (c). The white ellipse encircles the 4th rung that was released to simulate a ladder climbing misstep.

Participants climbed the ladder 30 times in both climbing directions, across three glove conditions as described in Section 4.3.3.2. Participants were asked to climb at a comfortable but urgent pace to simulate the climbing speed of a regular-to-busy work day. Participants experienced 6 ladder climbing misstep perturbations (i.e. releasing of the fourth rung), one for each condition

(2 climbing directions x 3 glove conditions). The order of the perturbation was randomized. Three to six regular (unperturbed) climbs were performed prior to each perturbation to reduce anticipation.

Two participants withdrew after two climbing perturbations (8 missing perturbations) and equipment malfunction of one participant prevented data collection of the last two perturbations. A total of 176 perturbations were analyzed (31 participants x 6 perturbations – 8 withdrawal – 2 equipment malfunction).

4.3.3.4 Data analysis

The mean breakaway strength was found for each participant per glove condition (averaged peak forces between hands and trials). Breakaway strength was normalized to participant body weight.

Fall severity was quantified as the peak force supported by the safety harness (referred to as harness force hereafter) between perturbation onset and end of perturbation (based on a local maximum of the harness force (Figure 4.1.2 [127]). An additional 9 trials were excluded due to incongruence in the selected peak between the algorithm and visual inspection. Harness force was normalized by body weight.

Hand-rung force was found for the moving hand (i.e. the hand that moved during/after the perturbation), next-moving hand (i.e. the hand that would have been next to move in cases where the hand did not move), non-moving hand and combined hands. The next-moving hand was classified separately from the non-moving hand due to differences in arm posture that are known to influence hand-rung force generation [84]. Specifically, after ascending perturbation the next-moving hand was lower than the non-moving hand and after descending perturbations the next-moving hand was higher than the non-moving hand (Figure 4.3.2). Classification of the moving and non-moving hand was kinematically determined from hand offsets/onsets of the 3rd metacarpal marker [128]. Individual hand-rung force (moving hand or non-moving hand) could only be found when one hand was in contact with the 8th or 9th rung (occurring 97 of 167 times for the moving and next-moving hand and 129 of 167 times for the non-moving hand). Combined hand-rung force could only be found if the hands were grasping the 8th and 9th rungs in a staggered hand placement (Figure 4.3.1.a) or both hands were grasping the 8th or 9th rung in a together hand placement (Figure 4.3.1.b) (occurring 110 of 167 times). Hand-rung force data was filtered using a 2nd order lowpass Butterworth filter with a cutoff frequency of 10 Hz [161]. The peak horizontal, vertical and resultant hand-rung forces of the moving and combined hands were found between hand onset following perturbation onset and peak harness force (Figure 4.3.3). The peak horizontal, vertical and resultant hand-rung forces of the next-moving and non-moving hand were found between perturbation onset and peak harness force.

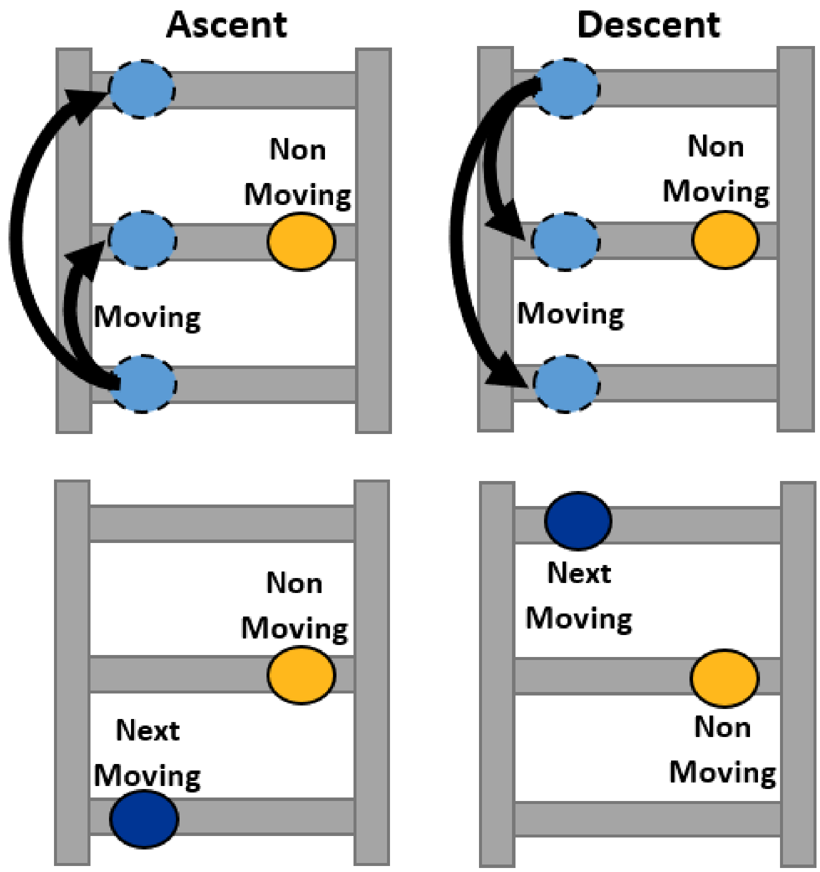


Figure 4.3.2: Schematic of hand placment after a climbing perturbation. The moving (light blue, dashed outline), next-moving (dark blue, solid outline) and non-moving (yellow, solid outline) hand placement after an ascending (left diagrams) and descending (right diagrams) perturbation. The typical unperturbed hand movement contacted every other rung, resulting in staggered hand placements. Common hand movements of the moving hand after a ladder climbing perturbation resulted in one of three hand placements [128] (top diagrams). The next-moving hand remained below the non-moving hand after an ascending perturbation (bottom left diagram), but above the non-moving hand after a descending perturbation (bottom right diagram).

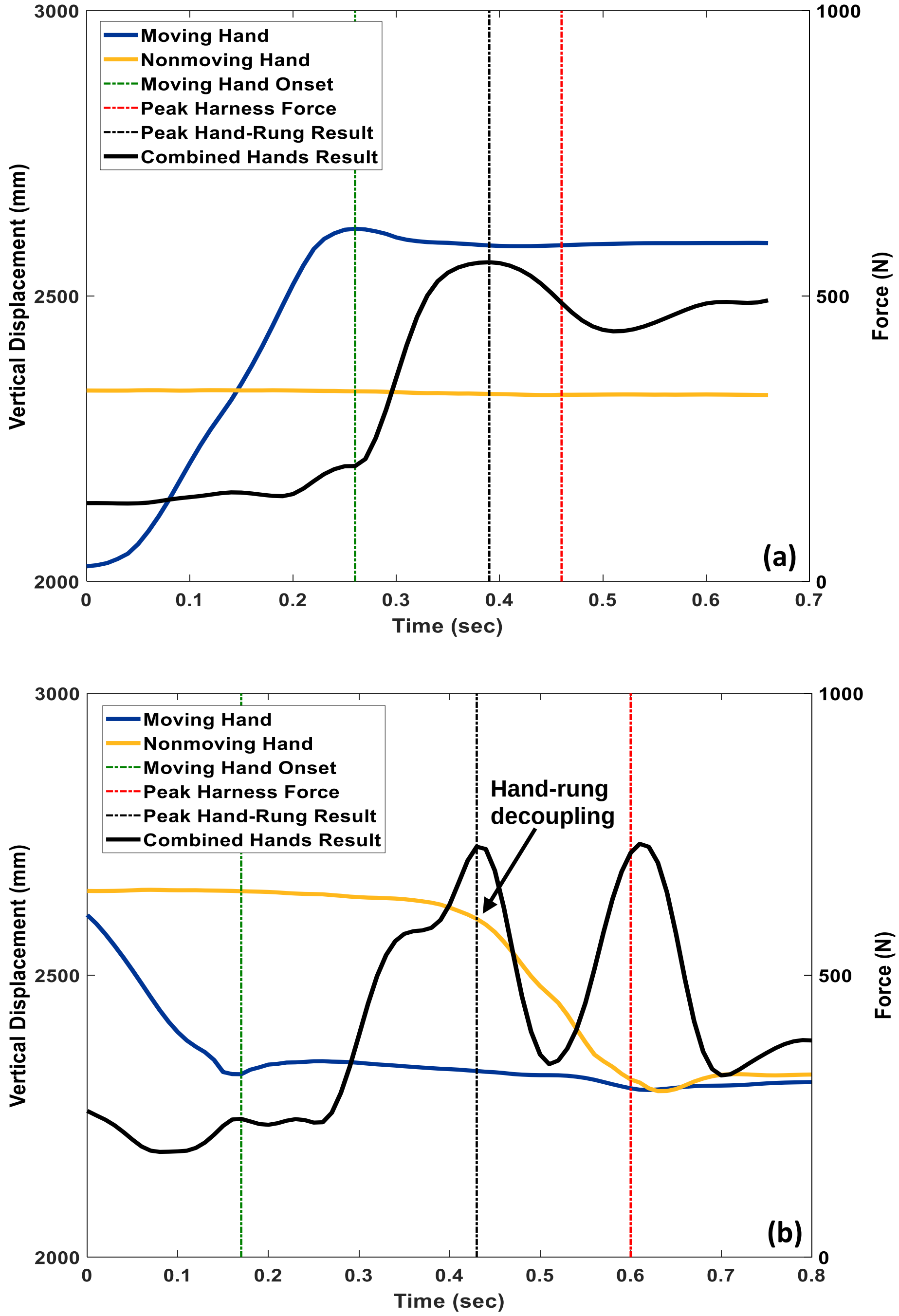


Figure 4.3.3: Time series of hand kinematics and kinetics. Displacement (left vertical axis) of the moving (solid blue line) and non-moving (solid yellow line) hands and resultant hand-rung force (right vertical axis) of the combined hands (solid black line) after an ascending (a) and descending (b) perturbation onset (time at zero). Vertical lines indicate time of moving hand onset (dashed green line), peak resultant hand-rung force (dashed black line) and peak harness force (dashed red line). The bottom graph (b) is a trial where the non-moving hand decouples from the rung. Peak hand-rung force occurs just prior to hand-rung decoupling.

The horizontal (horz) force was the sum of two load cells mounted horizontally on the left and right side of the 8th or 9th rung (Equation 4.1). Similar, the vertical (vert) force was the sum of two load cells mounted vertically on the left and right side of the 8th or 9th rung (Equation 4.2).

$$Horz\ \ Force = \frac{Horz_{left} + Horz_{right}}{Body\,Weight} \tag{4.1}$$

$$Vert\ \ Force = \frac{Vert_{left} + Vert_{right}}{Body\,Weight} \tag{4.2}$$

The resultant (result) force was obtained after summing the force vectors (Equation 4.3). The resultant force angle (Figure 4.3.1.a & Figure 4.3.1.b) was found at the time of peak resultant force (Equation 4.4).

$$Result\ Force = \frac{\sqrt{(Horz_{left} + Horz_{right})^2 + (Vert_{left} + Vert_{right})^2}}{Body\,Weight} \tag{4.3}$$

$$Result\ Force\ Angle = \tan^{-1}(\frac{Horz_{left} + Horz_{right}}{Vert_{left} + Vert_{right}}) \tag{4.4}$$

The hand-rung impulse and average hand-rung force was found to capture other aspects of the hands' contribution to recovery throughout the perturbation response [162, 164]. Specifically, the hand-rung impulse depicts the total hand-rung force contribution during the falling event, and the average hand-rung force reflects the efficiency in hand-rung force production (where higher forces can reflect faster rates to peak hand-rung force or consistently higher hand-rung force production).

The hand-rung impulse was found for the resultant hand-rung force from perturbation onset when the hand stayed in contact with the rung or hand onset when the hand moved (p1) to peak harness force (p2) (Equation 4.5). The average resultant hand-rung force applied was found by dividing the hand-rung impulse by the time duration of the applied hand-rung force (p2 – p1) (Equation 4.6). All hand-rung forces and impulses were normalized to body weight.

$$Impulse = \int_{p1}^{p2} Result\ Force * dt \tag{4.5}$$

$$Average\ Force = \frac{Impulse}{p2 - p1} \tag{4.6}$$

Two foot placement responses were observed [128]. Reestablished – at least one foot reestablished foot placement with a ladder rung; not reestablished – neither foot reestablished foot placement with the ladder rung(s). Foot-rung contact was kinematically determined from the three markers on the shoe (1st metatarsal, 5th metatarsal, and the most anterior and superior point of the shoe) and maintained foot placement was visually confirmed [128].

4.3.3.5 Statistical analysis

The mean and standard deviation of peak hand-rung force, hand-rung impulse and average hand-rung force of the moving, next-moving, non-moving and combined hands is reported. In addition, the mean and standard deviation of the peak resultant force angle is reported. All measures are reported by climbing direction.

To test the study hypotheses, linear regressions were performed with the normalized peak hand-rung force (resultant) of the moving, next-moving, non-moving and combined hands for each climbing direction as the dependent variable. Except, a linear regression was not performed for the next-moving hand after a descending perturbation, because the occurrence of the next-moving hand category was rare (only 7 cases). Normalized harness force (proxy measure of fall severity), normalized breakaway strength (proxy measure of upper body strength) and foot placement response were the predictor variables. Predictor variables with low correlation values were entered into models together ($r < 0.40$). Predictor variables with moderate to large correlations ($r \geq 0.40$) were entered into separate models [166]. Participant number was entered into the models as a random variable. Gender was treated as a covariate in the models (Table 4.3.1). Log transforms were performed on hand-rung forces to achieve normally distributed residuals. For congruency, hand-rung forces were compared with breakaway strength of the corresponding glove condition. A significance level of 0.05 was used. Statistical software (JMP®, Version 14. SAS Institute Inc., Cary, NC.) was used to perform analysis.

Table 4.3.1: Statistical analyses. The dependent and predictor variables in each statistical analysis. Additional test details are noted (separated test, random and confounding variables). Descriptive statistics on hand-rung force is a primary goal of this study and the linear regression model is a primary analysis to test the study hypotheses. Analyses were separated by climbing direction (ascent, descent) and hand classification (moving, non-moving, combined hands).

Analysis	Separated by	Dependent variable	Predictor variable	Other variable
Descriptive statistics	Climbing direction, hand classification	Peak hand-rung force, hand-rung impulse, average hand-rung force, peak resultant force angle	NA	NA
Linear regression	Climbing direction, hand classification	Peak hand-rung force	Harness force, breakaway strength, foot placement	Participant number (random), gender (confounder)

4.3.4 Results

4.3.4.1 Descriptive

The mean (standard deviation) normalized breakaway strength for males and females across all glove conditions was 0.79 (0.17) and 0.59 (0.16) body weight, respectively. The mean (standard deviation) harness force after ascending and descending perturbations was 0.18 (0.17) and 0.40 (0.29) body weight, respectively.

Hand-rung forces were greater after descending perturbations than ascending perturbations. The mean (standard deviation) peak resultant hand-rung force of the moving, non-moving and combined hands after an ascending perturbation was 0.50 (0.23), 0.59 (0.18), and 1.06 (0.34), respectively (shaded cells in Table 4.3.2). The mean (standard deviation) peak resultant hand-rung force of the moving, non-moving and combined hands after a descending perturbation was 0.59 (0.20), 0.75 (0.24), and 1.30 (0.24), respectively (non-shaded cells in Table 4.3.2) (Figure

4.3.4). The angle of the peak resultant force with respect to the vertical for the moving, non-moving and combined hands after an ascending perturbation was 16.0° (24.3°), 21.8° (10.6°), and 18.9° (7.7°), respectively. The angle of the peak resultant force with respect to the vertical for the moving, non-moving and combined hands after a descending perturbation was 19.8° (9.8°), 21.0° (6.5°), and 20.6° (3.7°), respectively.

Table 4.3.2: Hand-rung forces and angle of the resultant force. Mean (standard deviation) [95% Confidence Interval] normalized peak horizontal (horz), vertical (vert) and resultant (result) hand-rung forces and hand-rung force angle at peak resultant force after an ascending (shaded) and descending (non-shaded) perturbations for the moving, next-moving, non-moving and combined hands.

	Horz	Vert	Result	Angle at result	Horz	Vert	Result	Angle at result
Moving	0.18 (0.14)	0.52 (0.29)	0.55 (0.31)	11.5 (31.6)	0.18 (0.08)	0.51 (0.09)	0.54 (0.11)	17.2 (6.4)
	[0.12-0.23]	[0.40-0.63]	[0.43-0.68]	[-1.3-24.2]	[0.16-0.22]	[0.48-0.55]	[0.50-0.58]	[14.9-19.5]
Next-moving	0.20 (0.05)	0.42 (0.13)	0.46 (0.13)	19.7 (15.9)	0.42 (0.13)	0.75 (0.29)	0.84 (0.33)	31.8 (13.9)
	[0.18-0.22]	[0.38-0.47]	[0.41-0.50]	[13.9-25.4]	[0.30-0.54]	[0.48-1.02]	[0.53-1.15]	[19.0-44.6]
Non-moving	0.28 (0.23)	0.55 (0.06)	0.59 (0.18)	21.8 (10.6)	0.32 (0.20)	0.70 (0.08)	0.75 (0.24)	21.0 (6.5)
	[0.26-0.29]	[0.51-0.59]	[0.55-0.64]	[19.3-24.3]	[0.29-0.34]	[0.64-0.76]	[0.69-0.82]	[19.3-22.7]
Combined	0.41 (0.10)	1.00 (0.32)	1.06 (0.34)	18.9 (7.7)	0.48 (0.10)	1.21 (0.23)	1.30 (0.24)	20.6 (3.7)
	[0.38-0.43]	[0.92-1.08]	[0.98-1.15]	[17.0-20.8]	[0.45-0.51]	[1.14-1.28]	[1.22-1.37]	[19.5-21.7]

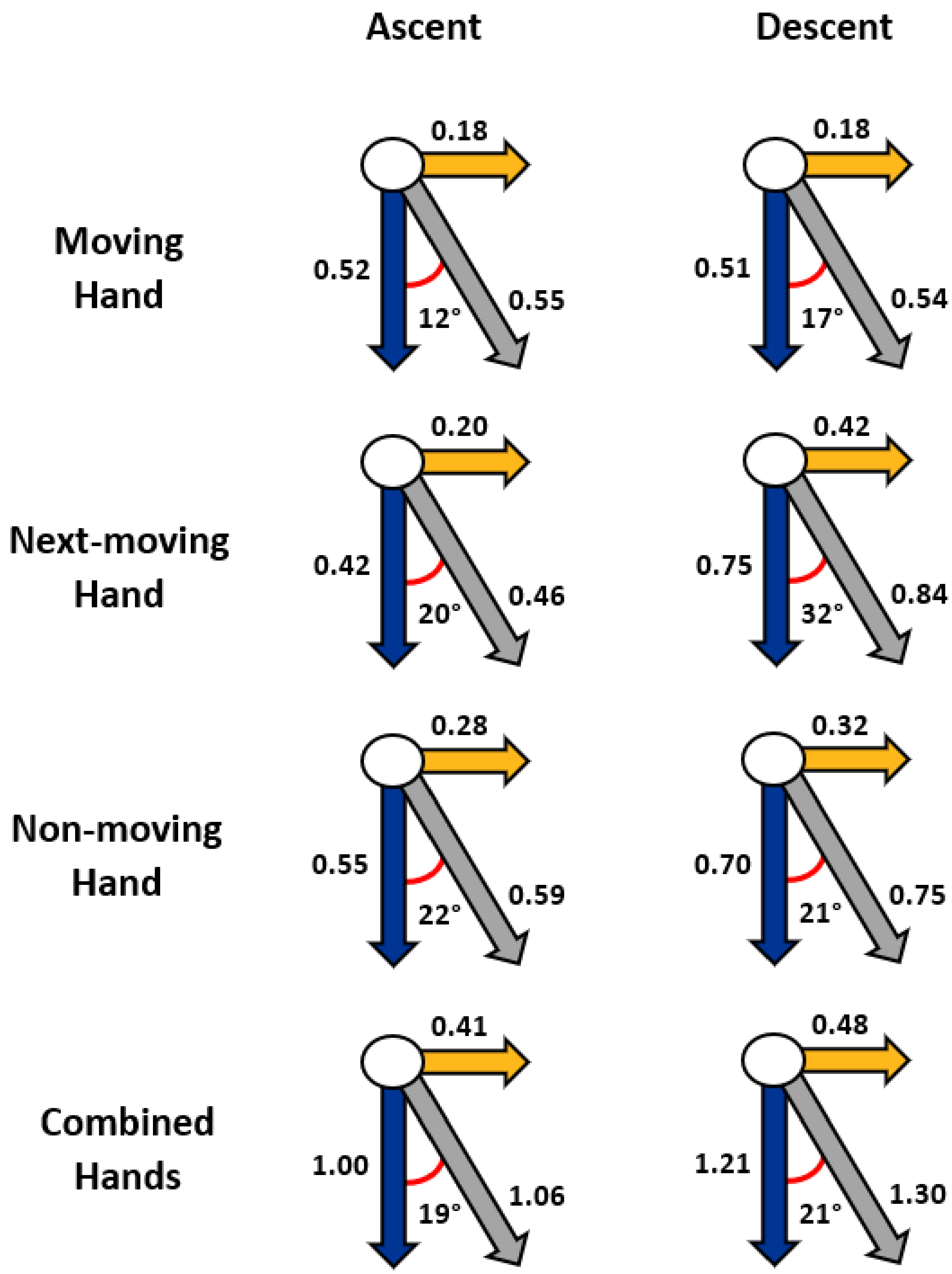


Figure 4.3.4: Schematic of hand-rung forces and angle of the resultant force. The mean peak horizontal (yellow arrow), vertical (blue arrow) and resultant (gray arrow) hand-rung force after ascending and descending perturbations for the moving, next-moving, non-moving and combined hands. Values are normalized by body weight. The mean peak resultant force angle with respect to vertical is denoted in degrees.

Hand-rung impulses and average resultant hand-rung forces were 25% to 108% and 10% to 70% greater after descending perturbations compared to ascending, respectively (Table 4.3.3). The hand-rung impulses (total contribution to recovery) and the average hand-rung force magnitudes (effectiveness of hand-rung force production) were observationally greater for the non-moving hand than moving hand.

Table 4.3.3: Hand-rung impulse and average hand-rung force. Mean (standard deviation) [95% Confidence Interval] normalized impulse and average resultant force applied between perturbation onset (or hand onset) and peak harness force after ascending (shaded) and descending (non-shaded) perturbations for the moving, next-moving, non-moving and combined hands.

	Impulse	Average	Impulse	Average
Moving	0.10 (0.09)	0.32 (0.15)	0.13 (0.05)	0.38 (0.08)
	[0.07-0.14]	[0.26-0.38]	[0.11-0.14]	[0.35-0.41]
Next-moving	0.13 (0.06)	0.27 (0.08)	0.27 (0.10)	0.46 (0.13)
	[0.11-0.16]	[0.24-0.30]	[0.18-0.37]	[0.35-0.58]
Non-moving	0.20 (0.08)	0.40 (0.08)	0.25 (0.08)	0.44 (0.10)
	[0.18-0.22]	[0.38-0.42]	[0.23-0.27]	[0.41-0.46]
Combined	0.31 (0.14)	0.61 (0.14)	0.39 (0.11)	0.70 (0.11)
	[0.28-0.35]	[0.58-0.64]	[0.36-0.43]	[0.67-0.74]

The hand decoupled from the rung in four perturbation trials (2 ascending, 2 descending). For ascent, in one case the moving hand decoupled (indicated by X in Figure 4.3.5.a-b) and in the other case the non-moving hand decoupled (indicated by X in Figure 4.3.5.e-f). In both ascending cases, foot placement was not reestablished. For descent, in both cases the non-moving hand decoupled (indicated by X in Figure 4.3.6.e-f). In one descending case, foot placement was reestablished, and in the other case, foot placement was not reestablished. Timing of peak resultant hand-rung force in decoupling cases occurred just prior to hand decoupling (peak force ranging from 51% to 150% of body weight), similar to the timing of peak hand-rung force in breakaway experiments [85] (Figure 4.3.3.b).

Reestablished and not reestablished foot placement occurred 57 (66%) and 30 (34%) times after an ascending perturbation, respectively. After a descending perturbation, reestablished and not reestablished foot placement occurred 55 (69%) and 25 (31%) times, respectively.

4.3.4.2 Predictors of hand-rung force

Harness force and foot placement were moderately correlated (r = 0.49) (Table 4.3.4) predictor variables after an ascending perturbation. Thus, these variables were assessed in separate regression models (model 1: harness force and breakaway strength; model 2: foot placement and breakaway strength). For model 1, the normalized hand-rung force of the next-moving (p = 0.007; $F_{1,27}$ = 8.69) (Figure 4.3.5.c), non-moving (p < 0.001; $F_{1,65}$ = 23.95) (Figure 4.3.5.e) and combined (p < 0.001; $F_{1,61}$ = 15.73) (Figure 4.3.5.g) hands increased with higher normalized harness force. Normalized hand-rung force of the moving hand insignificantly increased with normalized harness force (p = 0.105; $F_{1,22}$=2.87) (Figure 4.3.5.a). Normalized hand-rung force of the next-moving hand increased with breakaway strength (p = 0.046; $F_{1,27}$ = 4.38) (Figure 4.3.5.d). Normalized hand-rung force of the moving (p = 0.578; $F_{1,11}$=0.33) (Figure 4.3.5.b), non-moving (p = 0.655;

$F_{1,27}$ = 0.20) (Figure 4.3.5.f) and combined (p = 0.229; $F_{1,33}$ = 1.50) (Figure 4.3.5.h) hands was not influenced by normalized breakaway strength (Table 4.3.5). In model 2, reestablishing foot placement was associated with significantly lower normalized hand-rung force of the non-moving (p = 0.027; $F_{1,68}$=5.12) and combined (p = 0.015; $F_{1,61}$=6.24) hands. Foot placement was not found to significantly affect normalized hand-rung force of the moving (p = 0.376; $F_{1,14}$ = 0.84) and next-moving (p = 0.576; $F_{1,26}$=0.32) hands (Figure 4.3.7.a). In model 2, normalized breakaway strength did not influence the normalized hand-rung force of the moving (p = 0.024; $F_{1,19}$ = 0.88), next-moving (p = 0.159; $F_{1,28}$=2.10), non-moving (p = 0.243; $F_{1,26}$ = 1.43) and combined (p = 0.944; $F_{1,31}$ = 0.01) hands. Thus, Hypothesis 4.3.1 was not confirmed, while Hypothesis 4.3.2 was accepted for ascending perturbations. Gender did not influence hand-rung force in either model (Table 4.3.5).

Table 4.3.4: Correlations between predictor variables. Pearson's correlations between predictor variables after ascending (shaded) and descending (non-shaded) pertrubations. Moderate to large correlations ($r \geq$ 0.40) are in bold.

	Harness Force	Breakaway Strength	Foot Placement
Harness Force		0.33	**0.49**
Breakaway Strength	0.22		0.02
Foot Placement	0.14	0.04	

Table 4.3.5: Statistical outcomes from linear regression models after an ascending perturbation. *F*-value (*p*-value) of predictor variables in linear regression models of the moving, next-moving, non-moving and combined hand-rung force after an ascending perturbation. Model 1 (shaded) assessed the influence of harness force and breakaway strength on hand-rung force. Model 2 (non-shaded) assessed the influence of foot placement and breakaway strength on hand-rung force. Gender is included in both models as a confounding variable. Bold values indicate predictors with a *p* < 0.05.

	Harness Force	Breakaway Strength	Gender	Foot Placement	Breakaway Strength	Gender
Moving	2.87 (0.105)	0.33 (0.578)	0.08 (0.792)	0.84 (0.376)	0.02 (0.879)	0.30 (0.596)
Next-moving	**8.69 (0.007)**	**4.38 (0.046)**	0.01 (0.940)	0.32 (0.576)	2.10 (0.159)	0.15 (0.704)
Non-moving	**23.95 (<0.001)**	0.20 (0.655)	2.31 (0.145)	**5.12 (0.027)**	1.43 (0.243)	1.05 (0.318)
Combined	**15.73 (<0.001)**	1.50 (0.229)	0.22 (0.645)	**6.24 (0.015)**	0.01 (0.944)	0.01 (0.913)

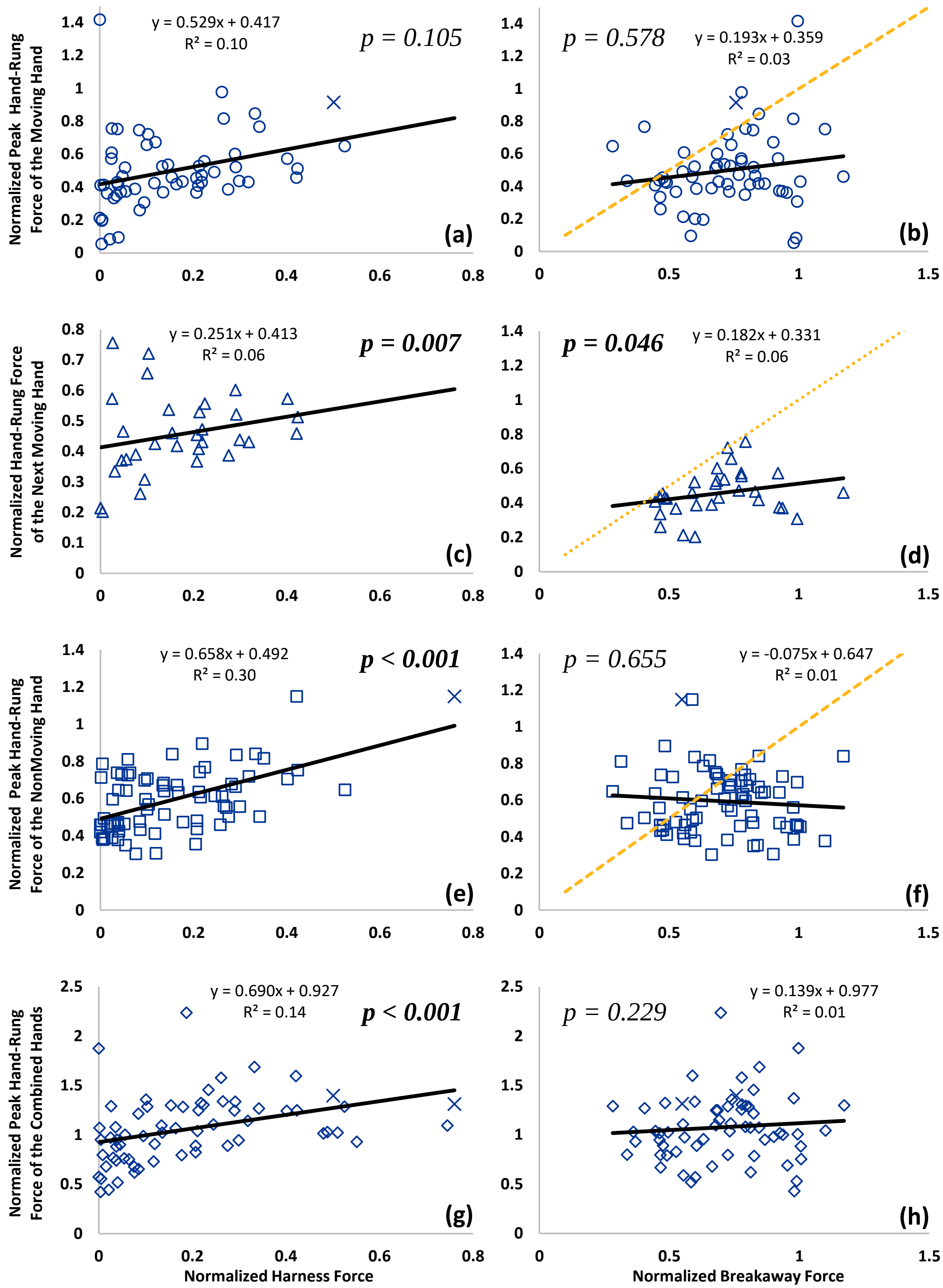


Figure 4.3.5: Hand-rung forces across harness force and breakaway strength after an ascending perturbation. Normalized peak resultant hand-rung force across normalized harness force (left side) and

normalized breakaway strength (right side) for the moving (circles) (a, b), next-moving (triangles) (c, d), non-moving (squares) (e, f) and combined hands (diamonds) (g, h) after an ascending perturbation. Peak resultant hand-rung forces are represented by body weight. Crosses (X) indicated trials where the hand decoupled. Linear best fit lines are solid. Peak resultant hand-rung force equal to breakaway strength is represented by a yellow dashed line. Data points above this yellow line indicate trials where the peak hand-rung force was greater than the participant's generated breakaway strength. This occurred in 8 trials (across 5 participants) for the moving hand and 18 trials (across 11 participants) for the non-moving hand. Depicted *p*-values are in regard to model 1. Bold *p*-values denote statistical significance.

No predictor variables had a moderate to large correlation after a descending perturbation (Table 4.3.4). Thus, one linear regression model was performed on hand-rung force after a descending perturbation with harness force, breakaway strength and foot placement as predictor variables. After a descending perturbation, normalized harness force was not associated with normalized hand-rung force of the moving (p = 0.307; $F_{1,3}$ = 1.45) (Figure 4.3.6.a), non-moving (p = 0.415; $F_{1,51}$ = 0.68) (Figure 4.3.6.e), and combined (p = 0.583; $F_{1,41}$ = 0.31) (Figure 4.3.6.g) hands. Normalized hand-rung force of the moving (p = 0.837; $F_{1,7}$ = 0.05) (Figure 4.3.6.b), non-moving (p = 0.582; $F_{1,32}$ = 0.31) (Figure 4.3.6.f) and combined (p = 0.207; $F_{1,16}$ = 1.73) (Figure 4.3.6.h) hands was not associated with normalized breakaway strength. While statistical analysis was not performed for the next-moving hand, trend lines reflected higher hand-rung force with higher harness force (Figure 4.3.6.c) and lower breakaway strength (Figure 4.3.6.d). Thus, Hypothesis 4.3.1 and Hypothesis 4.3.2 were not confirmed for descending perturbations. Normalized hand-rung force of the moving (p = 0.718; $F_{1,37}$ = 0.13) non-moving (p = 0.757; $F_{1,55}$ = 0.10) and combined (p = 0.801; $F_{1,44}$ = 0.06) hands after a descending perturbation was not associated with foot placement response (Figure 4.3.7.b). Gender did not influence hand-rung force after a descending perturbation (Table 4.3.6).

Table 4.3.6: Statistical outcomes from a linear regression model after a descending perturbation. *F*-value (*p*-value) of predictor variables in a linear regression model of the moving, non-moving and combined hand-rung force after a descending perturbation. The influence of harness force, breakaway strength and foot placement on hand-rung force is assessed. Gender is included in the model as a confounding variable. Bold values indicate predictors with a $p < 0.05$.

	Harness Force	Breakaway Strength	Foot Placement	Gender
Moving	0.46 (0.504)	2.53 (0.123)	0.13 (0.718)	0.99 (0.333)
Non-moving	0.68 (0.415)	0.31 (0.582)	0.10 (0.757)	<0.01 (0.981)
Combined	0.31 (0.583)	1.73 (0.207)	0.06 (0.801)	1.10 (0.313)

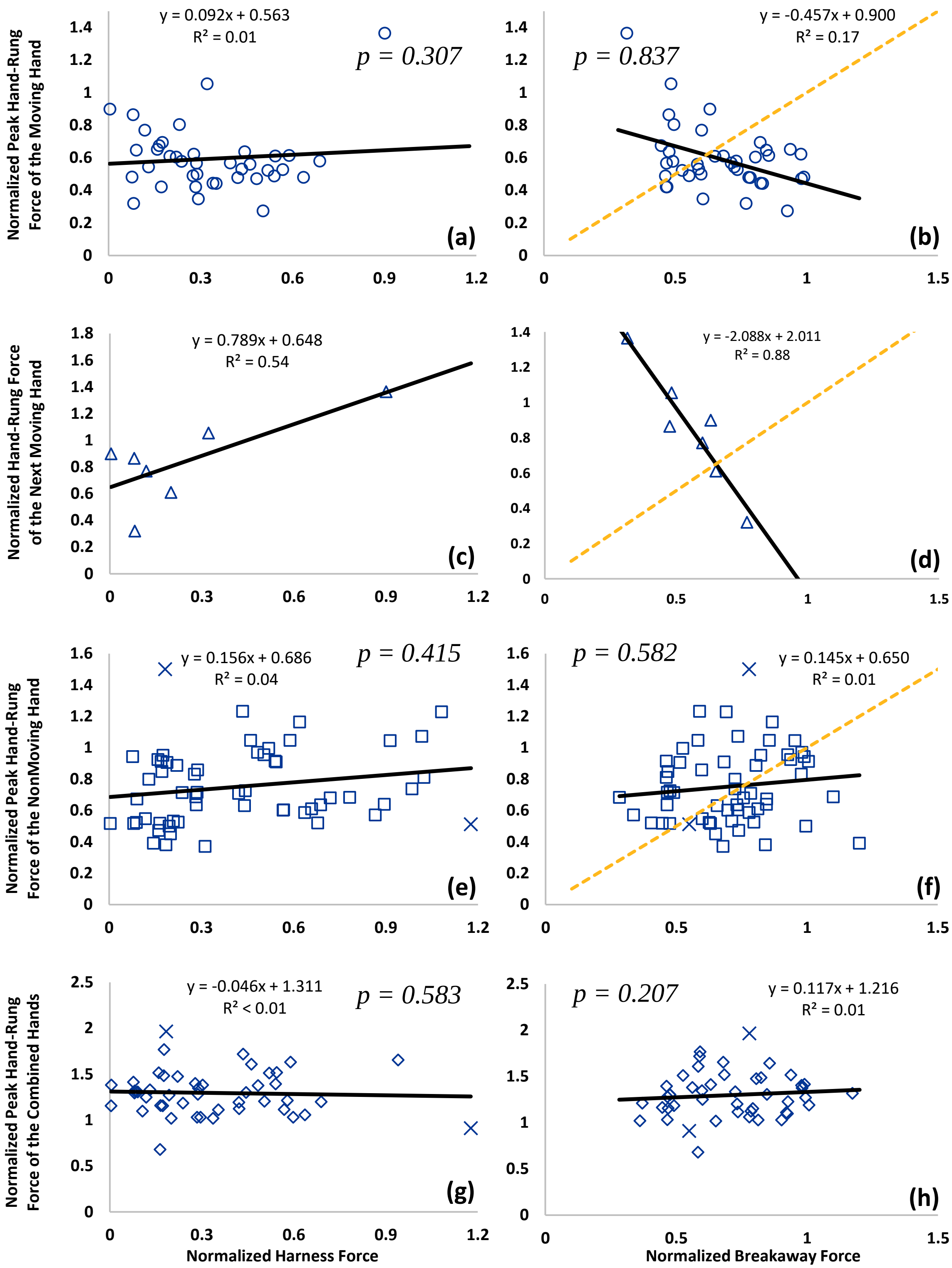


Figure 4.3.6: Hand-rung forces across harness force and breakaway strength after a descending perturbation. Normalized peak resultant hand-rung force across normalized harness force (left side) and normalized breakaway strength (right side) for the moving (circles) (a, b), next-moving (triangles) (c, d), non-moving

(squares) (e, f) and combined hands (diamonds) (g, h) after a descending perturbation. Peak resultant hand-rung forces are represented by body weight.Crosses (X) indicated trials where the hand decoupled. Linear best fit lines are solid. Peak resultant hand-rung force equal to breakaway strength is represented by a yellow dashed line. Data points above this yellow line indicate trials where the peak hand-rung force was greater than the participant's generated breakaway strength. This occurred in 11 trials (across 7 participants) for the moving hand and 29 trials (across 15 participants) for the non-moving hand.

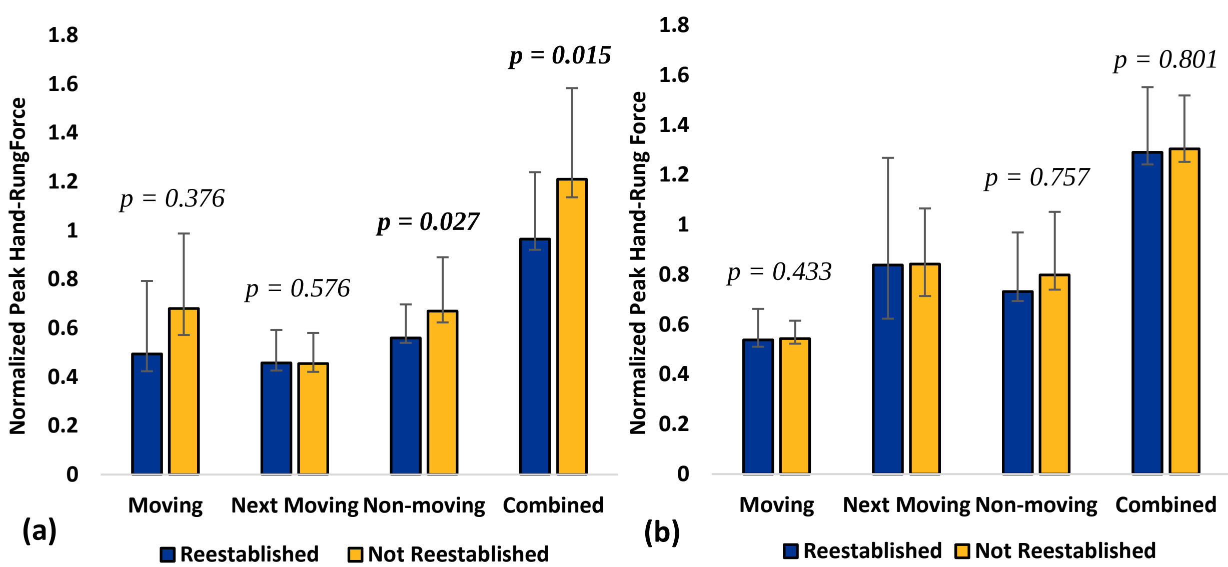


Figure 4.3.7: Hand-rung force by foot placement. Mean normalized peak hand-rung force of the moving, next-moving, non-moving and combined hands for reestablished (blue bars) and not reestablished (yellow bars) foot placement after ascending (a) and descending (b) perturbations. Peak resultant hand-rung forces are represented by body weight. The *p*-value of foot placement response on peak hand-rung force is displayed for each hand classification (excluding the next-moving hand after a descending perturbation). Positive error bars represent the standard deviation and negative error bars represent standard error. Bold *p*-values denote statistical significance.

4.3.5 Discussion

This work quantified the hand-rung forces utilized after a ladder climbing perturbation as approximately 46% to 84% of body weight. Increased hand-rung forces were clearly linked with greater fall severity (i.e. harness force) after ascending perturbations, but not descending perturbations. Individual upper body strength (measured via breakaway strength) was not found to consistently contribute to hand-rung force. Participants that reestablished foot placement utilized a lower hand-rung force after an ascending perturbation. Thus, this study supports hand-rung forces to be related to the circumstances of the fall (fall severity, foot placement) rather than individual capacity to generate force. Hand-rung forces after descending perturbations were not strongly predicted by any factors considered in this study.

The hand-rung forces observed in this study provide important context for interpreting hand force capacity values from other studies. The peak hand-rung forces after a climbing perturbation in this study ranged from 46% to 84% of body weight (depending on climbing direction and the hand). These values are similar to the force capacity observed during the breakaway strength test from the present study and were just below the force capacity values reported in Young et al. 2009 for horizontal rungs (Figure 4.3.8). Furthermore, handhold designs that are associated with dramatic reductions in force capacity may inhibit the body from achieving the forces required to recover from ladder climbing perturbations. For example, a vertical plate approximately halves force capacity relative to a horizontal cylindrical rung [87], which could lead to insufficient force capacity to respond to a climbing perturbation. Presumably, inhibiting the forces generated by the hand would increase fall risk. Thus, this data supports the relevance of studies that quantify force capacity across different ladder handhold designs.

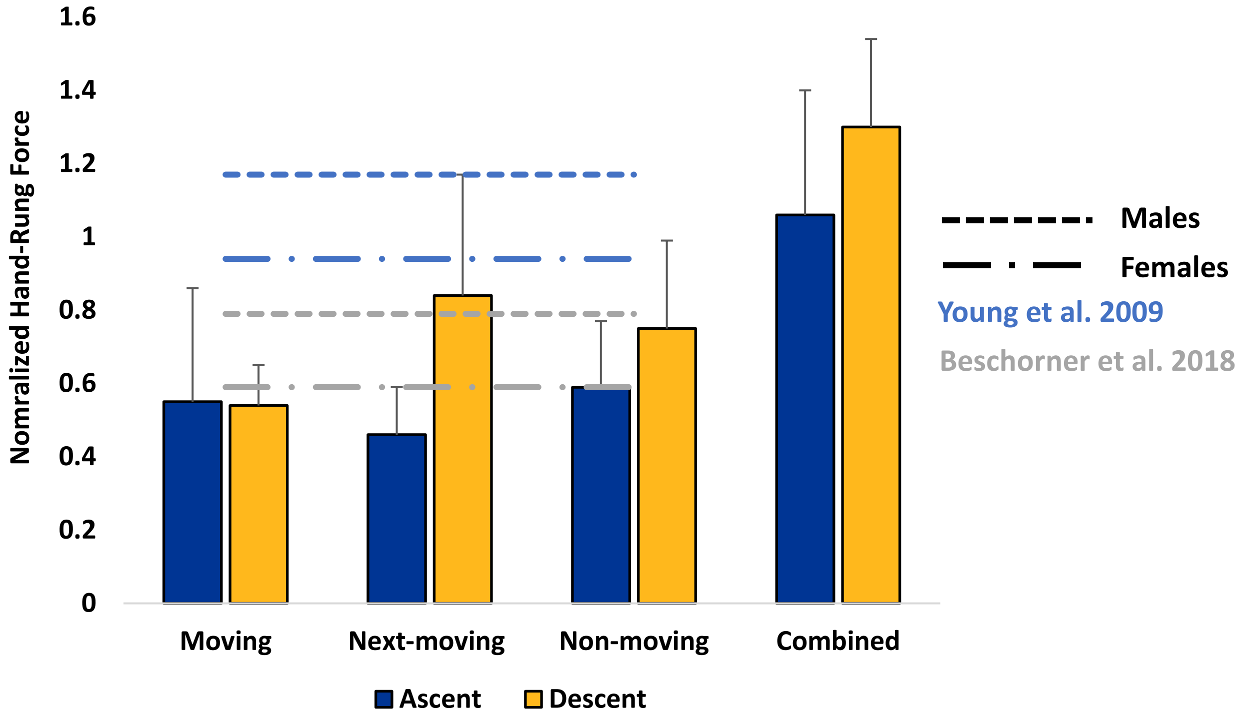


Figure 4.3.8: Hand-rung force and breakaway strength comparison. Mean normalized peak hand-rung force for the moving, next moving, non-moving and combined hands after an ascending (blue bars) and descending (yellow bars) climbing perturbation. The mean normalized peak force generated onto a rung in breakaway strength tests for males (dashed line) and females (dash-dot line) in the Young et al. 2009 [87] and Beschorner et al. (2018) (participants in this study) [84] cohorts is displayed on the plot. Hand-rung forces after a climbing perturbation are approaching and in some cases exceeding force values prior to hand-rung decoupling in breakaway strength tests. Error bars denote standard deviations.

Furthermore, the mean peak resultant hand-rung force utilized after a ladder climbing perturbation are up to 2.8 times greater than the mean peak resultant hand-rung force utilized during unperturbed climbing (30% to 42% of body weight) [72, 76]. This increase is largely contributed by an increase in the vertical hand-rung force (42% to 75% of body weight after a perturbation) after a climbing perturbation, whereas the horizontal hand-rung force (18% to 42% of body weight after a perturbation) remains closer to the vertical and horizontal hand-rung force for unperturbed ladder climbing (approximately 18% of body weight) [72, 76]. Current ladder handhold designs are sufficient for supporting hand-rung force during unperturbed climbing. However, peak hand-rung forces utilized after a climbing perturbation and four hand decoupling cases in the study suggest that ladder handhold designs are not always satisfactory in preventing hand decoupling after a ladder climbing perturbation.

This study used peak hand-rung force as the primary outcome measure because this measure is most relevant to forces exerted prior to hand-rung decoupling [84, 85, 87]. The impulse and average hand-rung force values were also reported to quantify other characteristics of the hand-rung interaction. These additional metrics revealed that the impulse and average force was observably higher for the non-moving hand than the moving hand. These findings may be influenced by the moving hand having less time in contact with the ladder rungs. The longer hand-rung contact time for the non-moving hand contributes to the greater force contribute to fall recovery (i.e. hand-rung impulse). However, the non-moving hand was also observably more effective in generating greater force when normalized to hand contact time (i.e. average hand-rung force). Perturbation research on stair handrails have assessed the peak handrail force [163], handrail impulse [164] and average handrail force [162] to interpret their results. While there are differences between these three metrics (peak, impulse and average force), these variables were, for the most part, well correlated (Appendix C.4.13). Thus, factors that influence one of these variables (peak force) are likely to also influence the other metrics (impulse and average force).

This study tested two competing hypotheses investigating the relationship of upper body strength and fall severity with hand-rung force. The results indicate that fall severity contributes more to the generated hand-rung force than strength, at least after ascending perturbations. This conclusion is based on the consistently positive correlation between hand force generation and fall severity, a trend that was not observed for breakaway strength. Furthermore, the R^2 values were substantially higher for the models that included fall severity than those that included breakaway strength. Thus, the hand may be reactively generating force than proactively producing hand-rung force based on strength capacity. This suggests that hand-rung force is partially due to the severity of the falling event (predicting 6% to 30% of hand-rung forces) after an ascending perturbation. This is similar to fall research with balance [167] and gait [168] perturbations, where an individual's lower body recovery response is dependent on perturbation difficulty or severity. Therefore, the body may detect fall severity and scale the body's motor response respectively. Hand-rung forces after a descending perturbation were not predicted by fall severity or upper body strength. Arresting a descending ladder climbing perturbation is more challenging than arresting an ascending climbing perturbation, as shown by a greater downward momentum and fall severity for descending perturbations [127]. The limited number of successful fall recoveries (as indicated by < 30% of body weight supported by the harness [142]) after a descending perturbation in this study, impose difficulties in identifying relevant recovery factors. Descending perturbations may be too challenging of a task with less allotted time to respond before falling into the harness. Previous research has found higher hand placements after a descending perturbation to reduce fall severity [128], but future work should investigate ladder fall interventions that can arrest the climber without the climber facilitating an active recovery response (e.g. an optimized ladder design to arrest descending perturbation).

An interesting trend was observed with the next-moving hand-rung force after a descending perturbation. While statistical analysis was not performed, individuals with greater upper body strength generated less hand-rung force for the next-moving hand than individuals with less upper body strength. Higher strength individuals may rely on only one hand (i.e. non-moving hand) to arrest their fall, whereas lower strength individuals may be required to utilize both hands to arrest their fall. This is biomechanically possible, for breakaway force experiments have shown participants to generate hand-rung force greater than their body weight [85, 87].

Participants that reestablished at least one foot back onto the ladder rungs after an ascending perturbation, utilized less hand-rung force than participants that did not reestablished their feet. Participants that reestablished foot placement may rely less on their upper body to arrest the falling event, because the feet are capable of supporting the majority of body weight [76]. Reestablishing foot placement can reduce the likelihood of hand decoupling by reducing reliance on the hand. Slightly less hand-rung force was utilized after a descending perturbation for reestablished than not reestablished foot placement, but the effect was not significant. This analysis may be underpowered to determine the influence of foot placement on utilized hand-rung force after a descending perturbation.

There are limitations in this study. This is an exploratory analysis. A study designed to assess mechanisms (e.g. fall severity, upper body strength) and interacting factors (e.g. foot placement, gender) of hand-rung forces utilized after a ladder climbing perturbation is necessary to confirm these results. In addition, some analyses in this study may be under powered. Hand-rung force observed in this study may underestimate the true hand-rung force experienced after a ladder climbing perturbation because participants were caught in a harness for safety reasons. In addition, the medial-lateral horizontal and axial torque forces were not measured in this study and may give further insight on hand-rung kinetics after a climbing perturbation

This study quantified peak hand-rung forces utilized after a ladder climbing perturbation. This knowledge is necessary to evaluate the effectiveness of current ladder handhold designs on arresting a ladder falling event and preventing hand decoupling. In addition, this study investigated the relationship of fall severity and upper body strength with hand-rung force. Insight on factors that are associated with hand-rung force can guide future handhold designs (i.e. handholds that assist the climber in withstanding higher hand-rung forces as opposed to handholds that enable the climber to generate greater hand-rung forces). Lastly, this study found climbers who reestablish their feet back onto the ladder to rely less on generating hand-rung forces to arrest the falling event. This can help guide intervention that facilitate reestablished foot placement (e.g. wider rungs) to reduce risk of hand decoupling and falls from ladders.

5.0 Impact of Student-specific Content on Improving Student Engagement in a Biomechanics Outreach Program

This chapter investigates the effects of student-specific content on student engagement and performance. This chapter has been submitted for publication in a dedicated section to The Scholarship of Teaching and Learning in Biomechanics in the Journal of Applied Biomechanics [169]. Preliminary results for this chapter have been published through conference abstracts [170, 171]. Additional study methodology (Appendix D.1) and supplementary analyses (Appendix D.2) can be found in Appendix D.

5.1 Effects of Student Interests on Engagement and Performance in Biomechanics

5.1.1 Abstract

Women and minorities are not well represented among individuals earning degrees in engineering. This negatively impacts the relevance of engineered solutions to our diverse population. Student engagement towards math and science in high school is reflective of students pursuing Science, Technology, Engineering and Mathematics (STEM) degrees. Thus, there is a need for pedagogical techniques that increase student engagement among underrepresented groups in engineering. This study assesses the effects of student interests on engagement and performance in 10th grade students underrepresented in the STEM fields. Specifically, we assessed the effects of interest-tailored lectures on student engagement and performance in a 5-week program with bioengineering workshops. Thirty-one students receive interest-tailored lectures (intervention group) and 24 students received only generic lectures (control group). In addition, we assessed the effects of teaching method (lecture, classroom activities, laboratory tours) on student engagement. We found interest-tailored lectures to significantly increase student engagement in lecture compared to generic lectures. Students that received interest-tailored lectures had an insignificant, but meaningful 5% increase in student performance. Students rated laboratory tours significantly higher in engagement than other teaching methods (lectures, hands-on activities). Pedagogical techniques in this study can be used to increase engagement of underrepresented students in engineering. This may facilitate the needed growth of diverse students entering the engineering fields.

5.1.2 Introduction

The National Science Foundation (NSF) reports that 50% and 38% of the US population are women and underrepresented minorities (Hispanics, blacks, Asians, American Indians, Alaska Natives, Native Hawaiians, Other Pacific Islanders), respectively [90]. Yet, only 20% of bachelor's degrees in engineering are earned by women, and only 20% of bachelor's degrees in science *and* engineering are earned by minorities [90]. Low diversity in engineering has a negative impact on the relevance of engineered solutions. For example, little attention has been given to the safety of pregnant women with respect to the extent of motor vehicle crash research [172]. Consequently, 60% of traumatic injuries during pregnancy occur from motor vehicle crashes [173]. Furthermore, there is risk of unconscious bias from like-minded developers who are developing algorithms to infer population data. Specifically, estimated health measures of female and different ethnic populations are at increased risk of inaccurate representation [174]. Thus, there is a need to increase diversity in the engineering fields to facilitate engineering solutions that are appropriate for our diverse population.

The current theoretical process of becoming a scientist or engineer (referred to as the STEM pipeline) does not consider multiple pathways or reflect the learning style of women and underrepresented minorities [95, 175]. The STEM pipeline is linear in nature with required benchmarks (e.g. completing 8^{th} grade algebra, completing high school calculus, entering a STEM major), but fails to describe the experience of nearly half of the individuals that become scientists or engineers [175]. These failures are partly attributed to the neglect of motivation in pursuing a STEM degree and individual experiences [95, 175]. The pipeline ignores student engagement, which can be modeled as the product of student motivation and active learning experiences [176]. In practice, previous research has demonstrated success in engaging a diverse group of students in the STEM fields through student engagement techniques [94, 95]. Basing educational policies on a faulty pipeline leads to minimal growth in STEM professionals and limited diversity among those professionals [175], but student engagement techniques show potential to increase diversity of student representation. Therefore, increasing student engagement in engineering for young women and minorities is a promising method to grow diversity in the engineering fields. Below we outline the theory-based components, practice-related outcomes, and gaps in the literature on student engagement.

Student motivation, which is the product of student's expectation of success and value in what is being learned, has been shown to contribute to students' interest in earning STEM degrees [177-179]. Specifically, high school students that value and expect to succeed in science were more likely to rate STEM careers (scientist, engineer, computer scientist) higher than non-STEM careers for future interests [177]. Similarly, 8th grade students that expected to be in a science-related career and displayed high mathematical achievement were 2.6 times more likely to earn a STEM degree than students who did not expect to be in a science-related career and displayed lower mathematical achievement [179]. Furthermore, students' prior academic performance influences their expectations of success. Students with higher SAT math scores, high school percentiles and 1st semester GPAs in college are more likely to declare a STEM major and earn a degree in STEM [178]. Therefore, student expectation of success and value in engineering can influence student motivation in pursuing an engineering degree.

The impact of students' perceived value of STEM education has been overlooked. Student expectation of success and value in STEM are both critical components of student motivation, as student motivation does not occur if one of these components is absent [176]. Yet, the majority of educational curriculums are only focused on increasing student expectation of success (e.g. raising test scores and promoting advanced courses) [179, 180]. This is surprising, given the impact of student expectation in STEM (i.e. mathematical achievement level) and student value in STEM (i.e. students expecting to be in science-related careers) are similar [179]. A high expectation in STEM (regardless of value in STEM) or high value in STEM (regardless of expectation in STEM) were both associated with an additional 17% to 31% of students earning a bachelor's degree in STEM [179]. Thus, enhancing student value in engineering is a novel and potential pathway to increase student motivation in pursing an engineering degree.

Active learning occurs when the student's mind is active in the learning process. Thus, many teaching pedagogies have been designed to involve student thinking in the learning process (active learning activities include: muddiest point [181], think-pair-share [182], flipped classroom [183], guided hands-on activities [184]). From a cognitive psychology perspective, meaningful learning occurs when the student can build new information onto what they already know (i.e. building upon their own schema of how the world works) [176, 185]. Students remember information that is intuitive and meaningful, and transferring new information is feasible when students can create associations to connect new information to an existing schema [176]. Thus, memory and transfer are critical components of active learning. Additional features contribute to memory (e.g. iterations/practice) and transfer (e.g. emotions towards learning) in active learning, but this study will focus on making meaningful and associated connections to student schemata.

Prior work has used basketball [95], and arts and storytelling [94] to engage students in STEM. While these studies created diverse pathways for students to engage in STEM activities, interests are personal and all students may not relate to basketball, arts and storytelling. An opportunity exists for instructors to engage underrepresented students in the STEM fields by incorporating STEM activities related to current student interests [95]. Therefore, student interests may provide the necessary link to engage underrepresented students in engineering.

We propose to use student interests to increase student engagement and performance in biomechanics. Specifically, incorporating student interests into course content may assist students in making associations (i.e. transferring) and meaningful connections (i.e. remembering) with new biomechanics content to their existing schemata, facilitating active learning. Alternatively, or in addition to, using student interests may increase their perceived value in the biomechanics content that is being learned, leading to increased motivation. Increases in student engagement have led to increases in student performance [186]. Therefore, we believe targeting components of motivation and active learning will lead to an increase in student engagement, facilitating an increase in student performance (Figure 5.1.1).

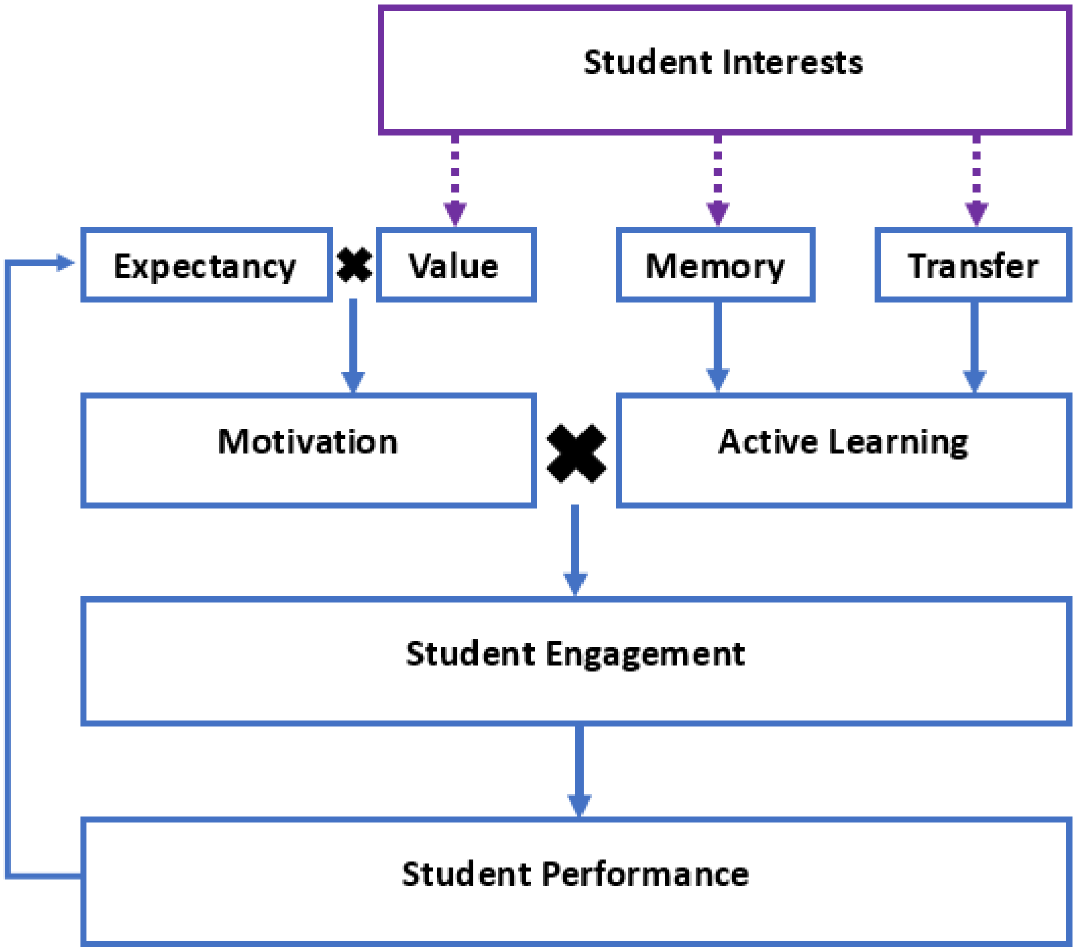


Figure 5.1.1: Model of student engagement. Solid arrows represent student engagement connections that have been previously established in literature. Dashed arrows represent the potential connections between student interests and student engagement.

This study will investigate effects on personal student interests on student engagement. Personal student interests will consist of lecture content that has been tailored to the students' specific interests (i.e. interest-tailored lectures). We will test the following hypothesis.

Hypothesis 5.1.1: Interest-tailored lectures will increase student engagement and performance.

In addition, this study will assess student engagement by teaching methods (lecture, classroom activities, laboratory tours). This will give further insight on student engagement across teaching method when incorporating interest-tailored lectures. Findings from this work will characterize the effects of student-specific content on student engagement and will reveal the effectiveness of student engagement across teaching methods.

5.1.3 Methods

5.1.3.1 Participants

Students underrepresented in the STEM fields were recruited to participate in a university STEM program. Specifically, the program was geared towards black, Latinx, Native American and female students in public schools near the university, but students from any gender or ethnic group could participate if they had a grade point average of 2.75 or higher with a 3.0 or higher in math and science. The STEM program is a 5-week college preparatory program between the months of June and July. Attendance is a full school day (9 am – 3 pm) for 4 days a week (Monday – Thursday). In the morning, students strengthened their course knowledge in mathematics, science and writing courses; whereas in the afternoon, they participated in engineering workshops. This study assesses student engagement and performance data from two 10^{th} grade cohorts that participated in the bioengineering workshops during 2016 and 2017. Only fully completed assessments were considered for data analysis, resulting in 23 and 31 student responses in 2016 and 2017, respectively. Approval was obtained by the Institutional Review Board at the University of Pittsburgh (#18120147). Investigators obtain non-sensitive, deidentified data to protect persons whose data were investigated.

5.1.3.2 Bioengineering workshops

The bioengineering workshops were 2 hours in duration, including a lecture and a hands-on activity. The environment of the bioengineering workshops was identical between the two cohorts. Specifically, the lecture was delivered via power point, and the lectures and hands-on activities were held in the same lecture and laboratory rooms. No additional incentives (e.g. candy) were given to the students to obtain classroom participation. Each week of the bioengineering workshop focused on a different discipline within bioengineering (Table 5.1.1).

Table 5.1.1: Bioengineering workshop disciplines. Disciplines studied in the bioengineering workshops by week.

WEEK	DISCIPLINE
1	Medical Devices
2	Neural Engineering
3	Tissue Engineering
4	Biomechanics
5	Ethics

This study investigates student-specific content outcomes from the biomechanics week (week 4). This week exposed the students to biomechanical applications in the fields of ergonomics/occupational safety, sports performance and orthopedics. In addition, the students toured two biomechanics laboratories, a motion capture laboratory and an orthopedic biomechanics laboratory at the university. The motion capture laboratory was equipped with force plates (Bertec Corp., Columbus, OH), a motion capture system (Vicon Motion Systems Ltd., UK), and electromyography with accelerometer sensors (Delsys Incorp., Natick, MA). The other laboratory was equipped with an Instron materials testing machine (Illinois Tool Works Inc., Norwood, MA), robotic actuators for simulating joints, and instruments for cadaveric tissue dissection to study tissue behavior. Students in the 2017 cohort (intervention group) received interest-tailored lectures for the biomechanics week and generic lectures for the other weeks. Students in the 2016 cohort (control group) received generic lectures for all weeks of the program.

5.1.3.3 Interest-tailored lectures

Interest-tailored lectures contained the same content as the generic lectures, but were tailored to the interests of the 2017 cohort. The 2017 cohort completed a form, prior to participating in workshop content, to identify their interests (Appendix D.1.1). These forms asked students to list careers, sports, athletes, video games, celebrities and other activities that were of interest to them. An average of 9 (range: 2 to 18) interests were reported by each student. From these forms, at least two (average of 5) interests of every student were included in the biomechanics lectures for the 2017 cohort. Student interests were used as visuals to aid in the explanation of biomechanical applications (Figure 5.1.2), importance of population-specific environments and products, functions of the musculoskeletal system, biomechanical instruments, and assessing biomechanical data (Table 5.1.2). For a few examples: recording studios with musical artists of different stature were used to show the importance of room layout (variability in microphone height) to reduce injury risk and increase task efficacy; a visual metaphor was provided relating the protection function of the military to the protection function of the musculoskeletal system; images of LeBron James running over a force plate and Kevin Hart standing on a force plate were used to discuss differences in ground reaction forces.

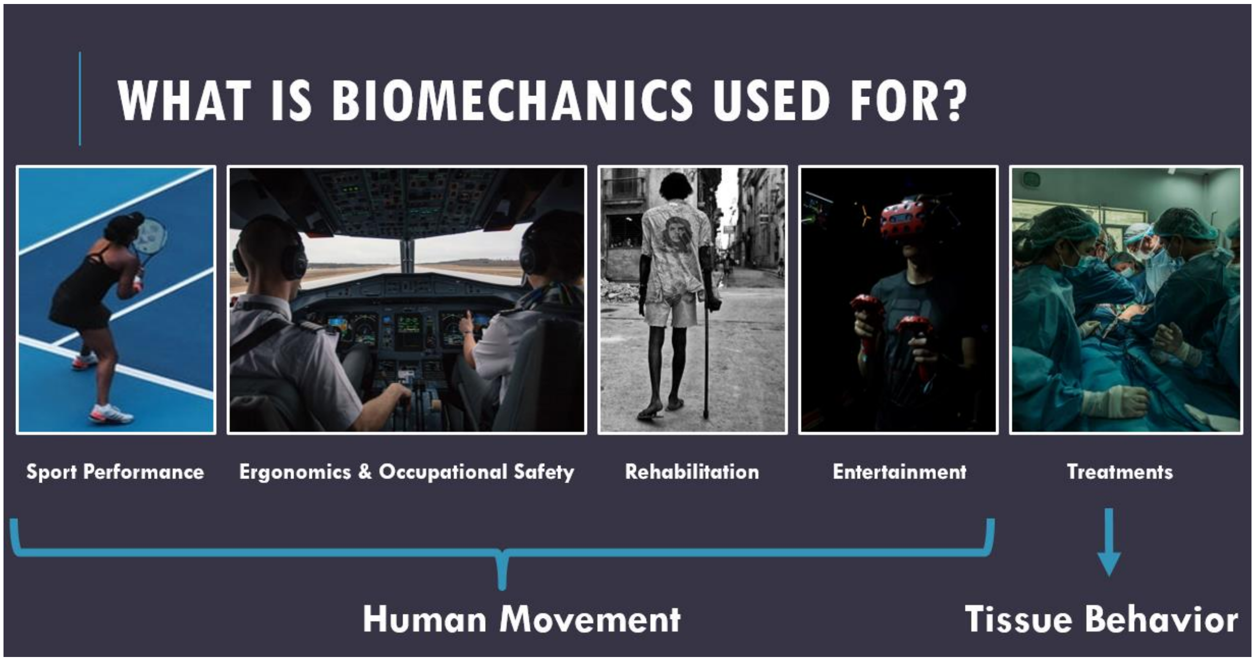


Figure 5.1.2: Interest-tailored lecture slide. An example of an interest-tailored slide on biomechanics applications. Images depicted in the slide were selected to apply content to student interests which include: tennis, aerospace engineering, video games and healthcare occupations (bioengineering, nursing, physician, anesthesiologist).

Table 5.1.2: List of student interests. List of student interests that were incorporated in the biomechanics lectures by category.

CATEGORY	STUDENT INTERESTS
CAREERS	Healthcare, military, computer programing, law, engineering, veterinarian, singing, acting, architect
SPORTS	Basketball, baseball/softball, football, tennis, hockey, track & field, swimming, soccer, volleyball, lacrosse, gymnastics
ATHLETES	Serena Williams, Odell Beckham Jr, Kris Bryant, LeBron James, Russell Westbrook, Sydney Leroux, Usain Bolt, Sidney Crosby, Simone Biles
VIDEO GAMES	Call of Duty/Battlefield, NBA 2K
CELEBRITIES	Chance The Rapper, Zac Efron, Kodak Black, Kevin Hart, The Rock
OTHER	Writing, art, singing, drawing, watching TV/Netflix/YouTube, movies

5.1.3.4 Student engagement assessment

Student engagement surveys were completed by the intervention group. The surveys asked the students four questions on 1) interest in biomechanics, 2) engagement in lecture, 3) enjoyment in the hands-on activities and 4) enjoyment in biomechanics laboratory (lab) tours. The students were asked to rate their agreement to the above statements using a 7-point Likert Scale. Likert responses were scored from -3 to 3 by an increment of 1 from strongly disagree to strongly agree (-3: strongly disagree, -2: disagree, -1: somewhat disagree, 0: neutral, 1: somewhat agree, 2: agree, 3: strongly agree). Students completed this survey twice, once at the beginning of the biomechanics week (pre interest-tailored lectures) and once at the end of the biomechanics week (post interest-tailored lectures). Thus, the first time the students took the survey, students were not asked about their enjoyment in lab tours (no tours were present in prior weeks), and the engagement in lecture and enjoyment in activities were in regards to the prior weeks with the generic lectures. The second time the students took the survey, students were asked about their enjoyment in lab tours, and the engagement in lecture and enjoyment in activities were in regards to the biomechanics week with interest-tailored lectures.

5.1.3.5 Student performance assessment

The control and intervention groups completed the same biomechanics quiz to assess student performance. The biomechanics quiz consisted of matching, multiple choice, calculation and open-ended questions. The students were also asked to complete a short essay on the importance of a biomechanics application of their choice (Appendix D.1.2). Students were scored on the percent of points obtained (20 points possible). In addition, both cohorts completed a pre-test at the beginning of the program (week 1) to assess their baseline knowledge of bioengineering.

5.1.3.6 Statistical analysis

Descriptive statistics (mean, median, standard deviation) were reported for student engagement questions to characterize student engagement across lecture type (generic, interest-tailored) and teaching method (lectures, activities, lab tours). Wilcoxon Rank-Sum tests were performed for the intervention cohort to assess whether a change in average response was observed using the student engagement survey for pre and post interest-tailored lectures. A Wilcoxon Rank-Sum test was performed for each survey question (excluding enjoyment in lab tours). Independent t-tests were performed to assess student performance between the control and intervention cohorts. One independent t-test was performed on the biomechanics quiz score and the other on the pre-test score (Table 5.1.3). A significance level of 0.05 was used. Statistical software (JMP®, Version 14. SAS Institute Inc., Cary, NC.) was used to perform analysis.

Table 5.1.3: Statistical analyses. The dependent and predictor variables in each statistical analysis. Additional test details are noted (separated test, random and confounding variables). The Wilcoxon Rank-Sum tests and independent t-tests were performed to test the study hypothesis. Descriptive statistics were calculated to provided additional context.

Analysis	Separated by	Dependent variable	Predictor variable	Other variable
Descriptive statistics	Lecture type, teaching method	Student engagment	NA	NA
Wilcoxon Rank-Sum test	Survey question	Student engagment	Lecture type	NA
Independent t-test	Pre-test/biomechanics quiz	Student perfromance	Intervention/control group	NA

5.1.4 Results

Students in the study were primarily from minority ethnicities and represented females and males (Table 5.1.4). Slightly more students identified as male in the 2016 cohort and more students identified as female in the 2017 cohort. The majority of the students identified as black in both cohorts.

Table 5.1.4: Student demographics. Demographics of the 2016 and 2017 cohorts. Values indicate the number of students

	MALE	FEMALE	BLACK	WHITE	ASIAN/ INDIAN	LATINX	MULTI-RACIAL
2016	12	11	18	3	1	0	1
2017	11	20	24	1	1	2	3

One student from the 2017 cohort did not complete the student engagement surveys. Thus, student engagement responses are assessed from 30 students. For pre interest-tailored lectures, the median student response was somewhat interested in biomechanics (Likert score = 1), somewhat engaged during lecture (Likert score = 1), and enjoyed the hands-on activities (Likert score = 2). Post interest-tailored lectures, the median student response was somewhat interested in biomechanics (Likert score = 1), engaged during lecture (Likert score = 2), enjoyed the hands-on activities (Likert score = 2), and strongly enjoyed the biomechanics lab tours (Likert score = 3) (Table 5.1.5, Appendix D.2.1). Thus, there was a noticeable increase in student engagement during lecture with interest-tailored lectures (median response change from somewhat engaged to engaged) (Appendix D.2.2). A noticeable change was not observed in the student median response for interest in biomechanics and enjoyment in hands-on activities with interest-tailored lectures. The median student response enjoyed the biomechanics lab tours more than the hands-on activities.

Table 5.1.5: Descriptive statistical outcomes of student engeagment. Mean [median] (standard deviation)

	Likert scores for student engagement questions			
	INTEREST IN BIOMECHANICS	**ENGAGED DURING LECTURE**	**ENJOYMENT IN ACTIVITIES**	**ENJOYMENT IN LAB TOURS**
PRE INTEREST-TAILORED LECTURES	0.70 [1] (1.34)	0.87 [1] (1.41)	1.43 [2] (1.41)	NA
POST INTEREST-TAILORED LECTURE	0.80 [1] (1.61)	1.73 [2] (1.05)	1.77 [2] (1.28)	2.36 [3] (0.87)

Interest-tailored lectures did not change interest in biomechanics (p = 0.606; $\chi^2_{1,30}$ = 0.267). Half of the 2017 cohort did not change their interest in biomechanics. One-third of students (10 of 30) increased their interest, while one-sixth of students (5 of 30) decreased their interest in biomechanics (Figure 5.1.3.a). Interest-tailored lectures significantly increased student engagement in lecture by 0.87 on the Likert scale (p = 0.014; $\chi^2_{1,30}$ = 6.018), partially confirming Hypothesis 5.1.1. The majority of students (60% or 18 of 30) found the interest-tailored lectures more engaging than the generic lectures. Thirty percent of the students (9 of 30) did not change their rating on lecture engagement, and 10% of students (3 of 30) showed a decrease in lecture engagement (Figure 5.1.3.b). Interest-tailored lectures insignificantly increased enjoyment in the hands-on activities (0.33 on the Likert scale) (p = 0.311; $\chi^2_{1,30}$ = 1.028). Only 43% of students (13 of 30) found increased enjoyment in hands-on activities, whereas 27% (8 of 30) and 30% (9 of 30) had no change or decreased enjoyment in hands-on activities (Figure 5.1.3.c), respectively.

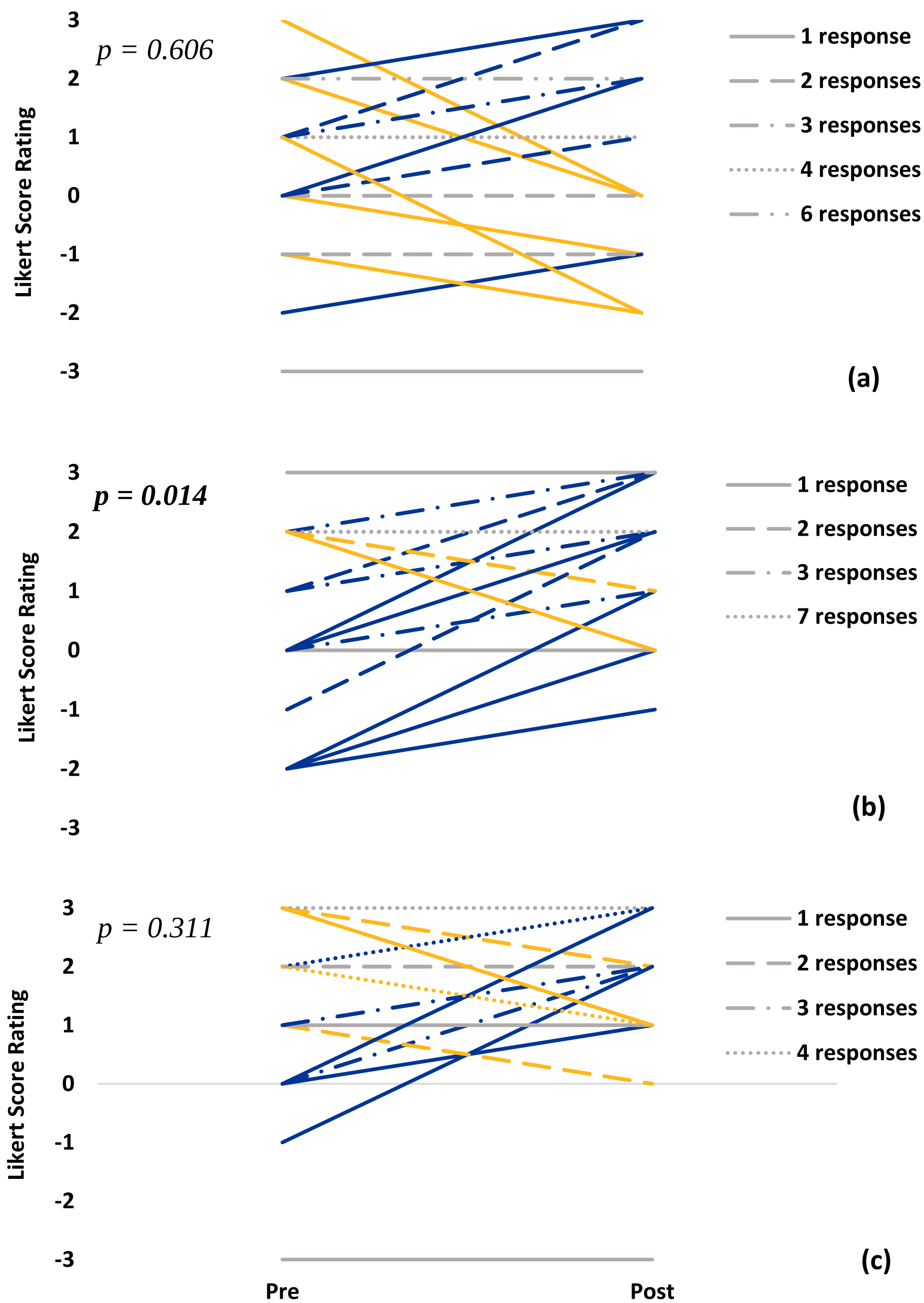


Figure 5.1.3: Student engagement responses. Student responses to interest in biomechanics (a), engagement during lecture (b) and enjoyment in activities (c) pre (left side of line) and post (right side of line) interest-tailored lectures. Line colors denote an increase (blue), decrease (yellow), or no change (gray) in Likert score rating from pre to post interest-tailored lectures. Line permeability corresponds to the number of students with the same pre to post response, denoted in the plot legend. Bold *p*-values denote statistical significance.

Pre-test scores were similar for students that received the generic lectures (scored 32% correct on pre-test) and interest-tailored lectures (scored 32% correct on pre-test) (p = 0.971; t_{42} = 0.04). Students that received interest-tailored lectures (scored 85%) scored 5% higher on the biomechanics quiz than the students that received generic lectures (scored 80%), but the change was not statistically significant (p = 0.239; t_{52} = 1.19) (Figure 5.1.4). Thus, Hypothesis 5.1.1 is partially rejected (no significant increase in student performance).

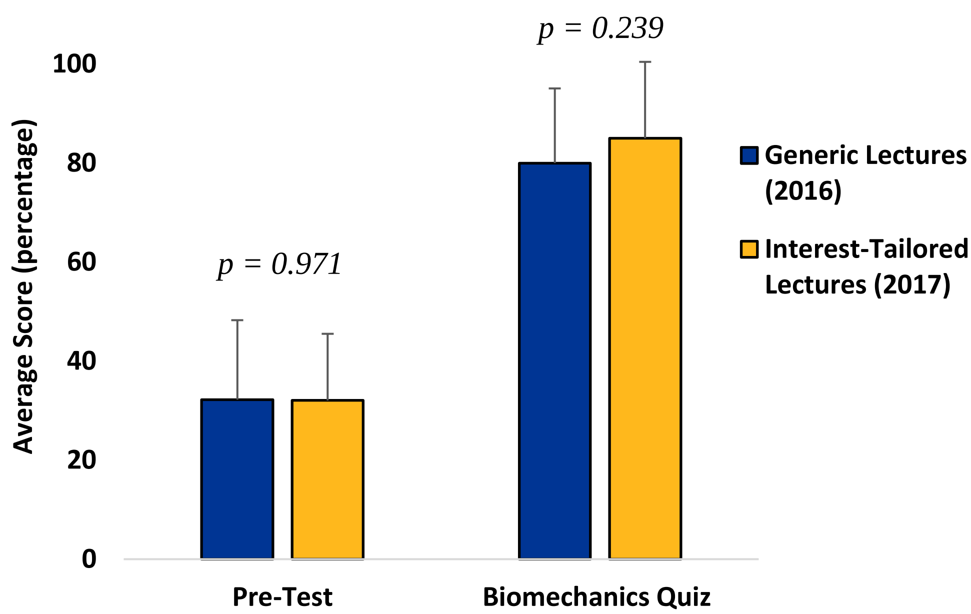


Figure 5.1.4: Pre-test and biomechanics quiz scores. Pre-test and biomechanics quiz scores for the students that received generic lectures (control group, blue bars) and interest-tailored lectures (intervention group, yellow bars). Error bars denote standard deviations.

5.1.5 Discussion

This study assessed the effects of including personal interests into course content on student engagement and performance in a 5-week bioengineering program. Personal interests (via interest-tailored lectures) were found to significantly increase student engagement during lecture. Including personal interests into the content increased student performance, but the increase was not significant. In addition, this study observed student engagement by teaching method. Students showed the greatest engagement in laboratory tours compared to other teaching methods (lectures and hands-on activities).

Utilizing students' personal interests increased the overall student engagement during lecture. The majority of students (60%) found the interest-tailored lectures more engaging than the generic lectures. For these students, student engagement may have been influenced from an increase in student motivation. Specifically, relating biomechanics content to the students' interests may have increased their perceived value of what was being taught [176]. Alternatively, or in addition to, building new biomechanics content onto their personal interests (i.e. existing schemata) may have engaged them in the active learning process by facilitating the transfer and memory of new knowledge [176]. Potentially, students may have had a greater interest towards the biomechanics content than the content of previous weeks. However, we do not believe this drove the increase in lecture engagement because students rated their engagement in lecture (1.73 on Likert scale) greater than their interest in biomechanics (0.80 on Likert scale), even after receiving interest-tailored lectures. Therefore, we believe utilizing students' personal interests is a promising pedagogical technique to increase student engagement. High student engagement (i.e. high motivation) in STEM is associated with students earning degrees in STEM [177, 178]. Thus, this technique can be used to target the interests of underrepresented students in engineering to increase diversity in the engineering fields.

Not all students showed an increase in lecture engagement with interest-tailored lectures. Of the nine students that did not change their rating on lecture engagement, eight of these students had also rated high engagement (Likert score of 2 or 3) during generic lectures. These students may be our "eager learners" who are typically engaged during class, regardless of how the content is delivered. Three students (10%) showed a decrease in lecture engagement. Thus, this pedagogical technique may not improve student engagement for every student. Some students may prefer more traditional teaching environments. Our results are similar to student perception on the flipped classroom, where 20% of students find the flipped classroom to not meet their learning needs [187].

Interest-tailored lectures did not increase student interest in biomechanics. The observed increases and decreases for interest in biomechanics maybe due to an increase in student knowledge on biomechanics applications. That is, some students may have been interested in biomechanics until they learned more about the field. While other students may have not been as interested in biomechanics until they learned more about the field. Undergraduate students have similar experiences through internships that refine their personal interests to their career ambitions [188]. While interest-tailored lectures did not increase overall student interest in biomechanics, this pedagogical technique may have assisted 50% of the 2017 cohort in refining their personal interests in biomechanics. Complete interest in biomechanics would have been remarkable, but is an unrealistic finding given known diversity in student interests [94].

A slight increase (0.33 on Likert scale) in enjoyment in hands-on activities was observed with interest-tailored lectures, but the increase was not significant. A small increase in student enjoyment on hands-on activities is not surprising, as only the lectures were enhanced with personal student interests. Incorporating personal interests in other aspects of teaching (class activities, homework, etc.) may further increase student engagement in these areas.

Students that received interest-tailored lectures scored 5% higher on the biomechanics quiz than students that received generic lectures. This agrees with the vast amount of literature that has reported improvements in student performance with increased student engagement [186]. Although the observed increase did not reach statistical significance, a 5% increase can be a meaningful outcome in an assessment grade (half a letter grade or 0.5 GPA boast). We have no evidence to support that differences in prior student knowledge influenced the higher quiz score in the interest-tailored group, because average pre-test scores were equivalent between the two cohorts. While not assessed in this study, improving student performance can feedback into student engagement by improving the student expectancy of success [176-178].

Students rated laboratory tours highest in engagement when compared to other teaching methods (i.e. lectures and hands-on activities). Visiting laboratories that were using biomechanics for real-world applications likely enhanced their perceived value of biomechanics, increasing student motivation. Furthermore, field trips (or laboratory tours) provide a platform for students to create personally relevant connections to prior experiences and learning [189], facilitating active learning. Therefore, providing real-world exposure in parallel to STEM content can enhance student engagement.

Students may find interest-tailored lecture as engaging as hands-on activities. Students rated hands-on activities higher in enjoyment than engagement in lecture pre interest-tailored lectures (a difference of 0.56 on Likert scale). Post interest-tailored lectures, the difference in engagement ratings between hands-on activities and lecture was small (a difference of 0.04 on Likert scale) (Figure 5.1.5). Therefore, utilizing personal interests in lecture may raise student engagement to a similar level of engagement that is perceived during hands-on activities.

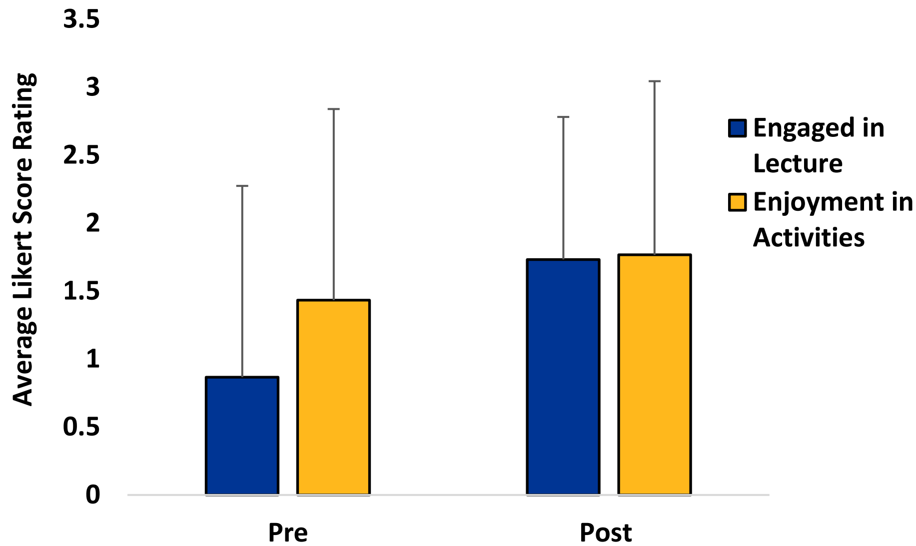


Figure 5.1.5: Student engagement responses by teaching method. Student responses (Likert score) for engagement in lecture (blue bars) and enjoyment in activities (yellow bars) pre and post interest-tailored lectures. Error bars denote standard deviations.

This study has limitations. Student engagement measures were self-reported. Objective measures of student engagement (e.g. number of students participating during lecture) are needed to support these findings. This study was not designed to test student engagement by teaching method (only observations reported). This study was also limited by sample size. Some overserved differences may have been statistically significant with a larger sample. This study did not directly assess components of student engagement (i.e. motivation, active learning). Further research (e.g. component specific questionnaires) is needed to delineate the connections between personal interests and the pathways to student engagement.

This study found personal interests (via interest-tailored lectures) to increase student engagement during lecture. The engagement rating during interest-tailored lectures was found to be similar to the level of student enjoyment during hands-on activities. Furthermore, students that received interest-tailored lectures had a meaningful improvement on student performance compared with the control, although the difference was not significant. When comparing student engagement across teaching method, students rated laboratory tours highest in engagement among other teaching methods (i.e. lectures and activities). Real-world exposure via laboratory tours provides students a platform to create personally relevant connections. Thus, this study highlights the importance of creating personal connections to facilitate student engagement. Incorporating student interests into teaching methods is a promising pedagogical technique to grow the diversity of students entering the STEM fields.

6.0 Conclusion and Final Remarks

This dissertation identified factors contributing to ladder falls and designed a pedagogical technique to improve student engagement in Science, Technology, Engineering and Mathematics (STEM). This work contributes to broader impacts on the safety and biomechanics fields.

The human factors approach (Figure 1.2.1) was utilized to investigate individual, environmental and biomechanical (i.e. interface between the individual and environment) factors associated with safe and effective ladder use and factors that aid in arresting a ladder fall. Knowledge gained from this approach is necessary to develop ladder fall interventions (e.g. screenings, improvements in safety standards, perturbation response training, ladder re-design) across multiple settings. This work is expected to have high societal impact to the safety field by reducing ladder fall injuries. Furthermore, this work adds knowledge to the biomechanics field from its novel experiments on ladder use and fall recovery.

Biomechanics was utilized as a link between student interests and the STEM fields to develop a student-interest based pedagogy technique to improve engagement of underrepresented groups in the STEM fields. Long-term effects from this work can increase diversity in the STEM fields and improve the equity in safety research.

6.1 Impact on Domestic Ladder Safety

Aim 1 of this dissertation investigated domestic ladder use among younger and older adults. This is the first study to assess ladder use of older adults. This work was necessary because domestic ladder fall rates are highest among older adults. Participants were asked to change a light bulb on a household stepladder under two cognitive demands. The cognitive demands consisted of a dual task (changing the light bulb while naming animals) and single task (changing the light bulb without a cognitive distraction). Ladder task performance was measured from a summative z-score based off the cohort's task completion time and standing stability. Two standing stability measures were assessed, center of pressure (COP) elliptical area and minimum COP to step edge distance. The summative z-score with elliptical area was defined as our traditional task performance measure, since elliptical area is a traditional standing stability measure. The summative z-score with edge distance was defined as our ladder specific task performance measure, since this measure is specific to the ladder task. That is, a smaller edge distance is associated with a more posterior COP displacement and increased risk of backwards balance loss. Key findings from this study are as followed:

- Clinically assessed balance was a primary predictor of ladder task performance among older adults. Specifically, a reduced sway path length when standing with eyes open on foam and a reduced number of errors in a coordinated stability task were associated with better ladder task performance. Balance was correlated with task performance regardless of task performance measure (traditional, ladder specific) and cognitive demand, and a predictor of task performance in three of the four models.

- Cognition, upper arm dexterity/coordination and age are secondary predictors of ladder task performance among older adults and displayed consistent correlations with task performance. Specifically, faster cognitive processing speed, better upper arm dexterity and coordination, and reduced age were associated with better ladder task performance. Cognition, upper arm dexterity/coordination and age were correlated with task performance regardless of task performance measure and cognitive demand, and a predictor of task performance in at least one of the four model.
- Edge contrast sensitivity and knee strength are secondary predictors of ladder task performance among older adults but displayed inconsistent correlations with task performance. Specifically, individuals with better contrast vision sensitivity and greater knee strength scored a better ladder task performance score. Edge contrast sensitivity and knee strength had inconsistent correlations with task performance across task performance measure and cognitive demand but were predictors of task performance in at least one of the four model.
- Older and younger adults did not significantly vary in standing COP elliptical area during the ladder experiment.
- Older adults displayed a smaller edge distance than younger adults by 17 mm and 4 mm for the single and dual task, respectively. This difference is meaningful to the base of support, representing up to 24% of the remaining posterior edge distance for older adults. This suggests that older adults exhibit more risky standing posture on a stepladder and are more likely to experience a ladder fall from backward balance loss.
- Younger adults completed the ladder tasks faster and had a faster animal naming rate for the dual task condition than older adults.

- Time to complete the task increased for both younger and older adults when completing the dual task, suggesting their cognitive resources were limited and subjected to resource competition.
- Older adults prioritized balance over additional tasks. This is shown by no change in balance performance between the single and dual task conditions.
- Younger adults prioritize additional tasks over balance. This is shown by reductions in balance performance during the dual task condition.

Knowledge of factors associated with safe and effective ladder use from Aim 1 (Figure 6.1.1) can guide ladder fall interventions. Such interventions may be in the forms of health screenings, ladder redesign and safety instruction.

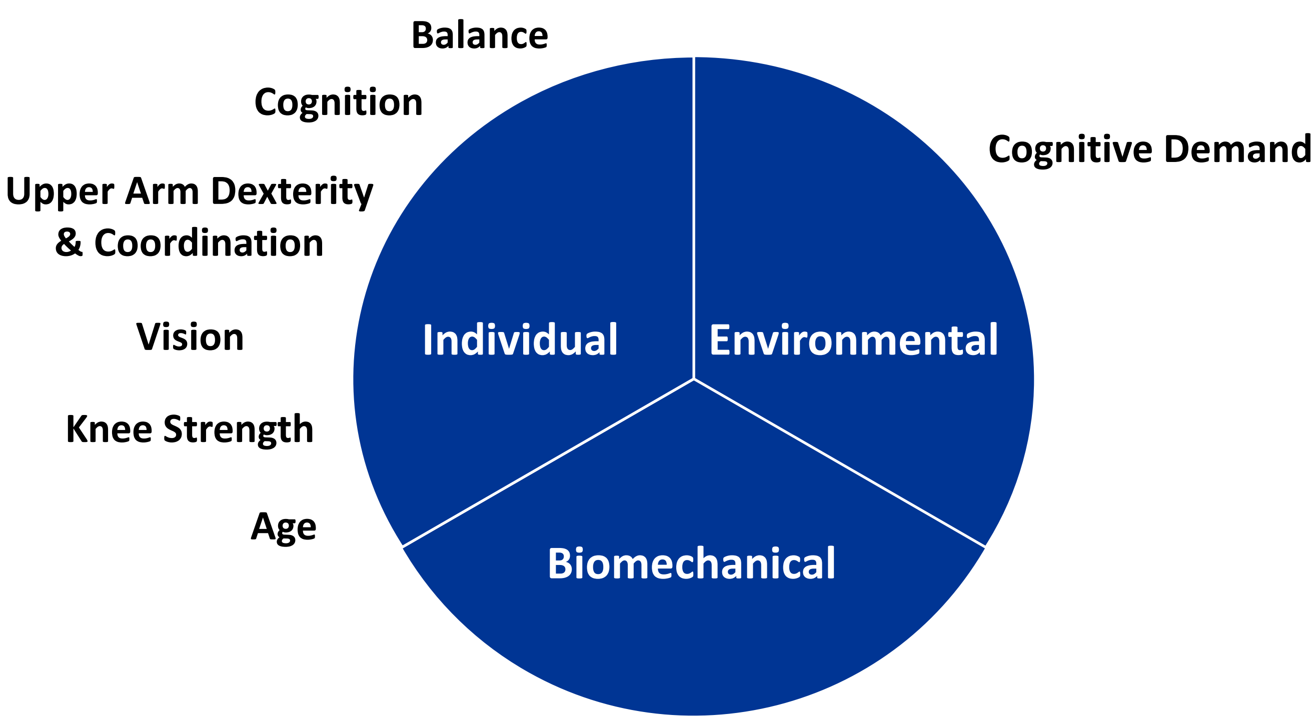


Figure 6.1.1: Summary of factors associated with safe and effective ladder use.

Health screenings:

- Individuals can be screened for ladder fall risk from a set of measures that are associated with safe and effective ladder use (i.e. task performance). This screening assessment may choose to measure individual sway on foam, cognitive processing speed, upper arm dexterity and coordination, edge contrast sensitivity and knee strength. These measurements may be weighted in the assessment (i.e. sway has a stronger correlation with ladder task performance than edge contrast sensitivity) to better assess ladder fall risk. Informing individuals of their ladder fall risk may aid them in determining ladders that are appropriate for their skill level.

Ladder redesign:

- A stepladder with a larger base off support can be provided for household or geriatric ladder users to reduce the potential of adverse events due to poor balance.
- Ladders can be redesigned to reduce the need of knee strength and balance via a forward lean support.

Safety instruction:

- Safety instructions can be updated to inform users to not work on the ladder while distracted.
- Safety instructions can provide solutions (e.g. tools, equipment) that reduce the need for skilled upper arm dexterity and coordination.
- Safety instructions can be personalized to age group. Informing ladder fall risk factors by age group.

Therefore, knowledge of individual factors that influence ladder task performance in this study can aid in reducing ladder fall injuries. However, additional knowledge is needed on individual factors that influence ladder use across different ladder types and tasks.

6.2 Impact on Occupational Ladder Safety

Aim 2 of this dissertation investigated individual, environmental and biomechanical factors on ladder fall severity after a climbing perturbation. This is the second study to facilitate a ladder climbing perturbation. This work is necessary to confirm mechanisms that contribute to ladder falls. Participants completed 30 ascents and descents on a vertically fixed ladder. A misstep perturbation was simulated by releasing the rung below the load supporting foot. Participants experienced a total of 6 climbing perturbation, one per glove condition (bare hands, low friction, high friction) in each climbing direction (ascent, descent). Climber fall severity was quantified from the load supported by the safety harness. Biomechanical recovery responses were recorded from markers and a motion capture system and load cells on the ladder rungs. Key findings from this study are as followed:

- Fall severity is higher after a descending perturbation than ascending. Recovering from a descending climbing perturbation is more challenging than an ascending climbing perturbation.
- Fall severity was higher for females than males. Recovering from a ladder climbing perturbation is more challenging for females than males.
- Glove condition did not affect fall severity.

- Fall severity was higher for females on their second and third climbing perturbation. Females may explore other fall recovery strategies before settling on one.
- Upper body strength, hand placement and foot placement are predictors of ladder fall severity.
- Individuals with greater upper body strength have a lower fall severity.
- Reestablishing higher hand placement after a climbing perturbation reduces fall severity.
- Reestablishing foot placement of at least one foot after a climbing perturbation reduces fall severity.
- Upper body strength assessed from a portable grip dynamometer is just as effective as a laboratory-based experiment (i.e. breakaway strength test) at predicting ladder fall severity.
- Hand-rung forces approach, and in some cases exceed, hand-rung breakaway forces. Ladder handholds may be sufficient for unperturbed ladder climbing, but insufficient for arresting a ladder falling event.
- Higher hand-rung forces are associated with a higher fall severity. Hand-rung forces were not strongly influenced by individual upper body strength.
- Individuals that reestablished foot placement had lower hand-rung forces than individuals that did not reestablish foot placement.
- Hand-rung forces are dependent on the circumstances of the fall (i.e. fall severity and reestablished foot placement).

Knowledge of factors that contribute to arresting a ladder fall from Aim 2 (Figure 6.2.1) can guide ladder fall interventions. These interventions can be in the forms of health screenings, personal protective equipment (PPE), training programs, ladder redesign and safety standards.

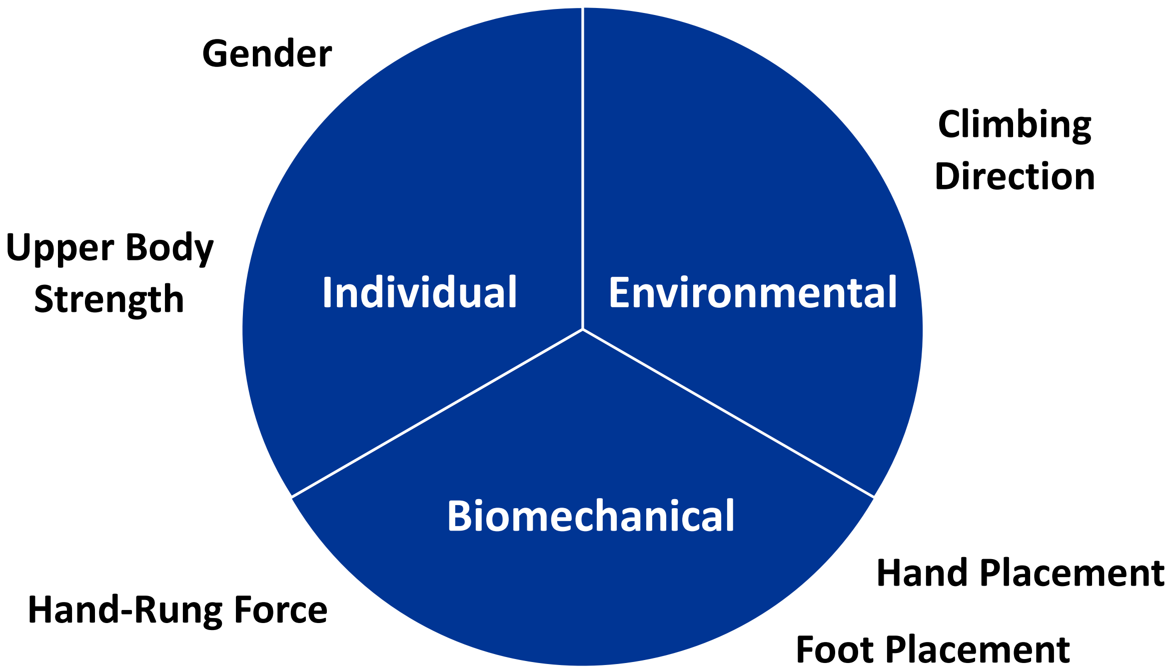


Figure 6.2.1: Summary of factors that contribute to arresting a ladder fall.

Health screenings:

- Individuals at increased ladder fall risk can be screened from an upper body strength assessment, such as a portable grip dynamometer that can be taken on-site. These individuals can be identified and provided with additional protective equipment and/or training.

Personal protective equipment (PPE):

- Females and lower strength individuals can be provided with additional protective equipment (e.g. safety harness, spotter, impact mat) during ladder use.

Training programs:

- Additional training and caution toward descending ladder climbs can be provided.

- Strength training and weight loss programs can be provided to ladder users to increase their ability to recover from a ladder climbing perturbation.
- Ladder fall perturbation training can be used to reduce exploratory responses of a “novel” falling event to improve recovery responses after a climbing perturbation.
- Ladder fall perturbation training can be used to promote effective hand and foot placement responses for ladder fall recovery.

Ladder redesign:

- Lower ladder rungs/steps can be redesigned (i.e. wider flat rung/step) to facilitate reestablished foot placement.
- Fixed ladders can be installed on a slight angle to promote reestablished hand and foot placement.
- Ladders can be customized to the ladder user. That is, not one ladder fits all. Ladders can be designed for ladder users of different heights. This may better enable females (and other shorter climbers) to reestablished higher hand placement and reestablish foot placement after a ladder climbing perturbation.
- Designing ladder handholds that are effective for arresting a ladder fall (i.e. withstanding high hand-handhold force as oppose to handholds that enable the climber to generate high force) and reduce the potential for hand-handhold decoupling.

Safety standards:

- Standards can be implemented to require ladder manufacturers, ladder users and employers to provide these above resources.

Knowledge from these studies can guide multiple ladder fall safety interventions to reduce ladder fall injuries. Thus, future work is needed to test the effectiveness of these interventions on improving ladder safety and reducing ladder fall injuries.

6.3 Impact on STEM

Aim 3 of this dissertation investigated the effects of student-specific content on student engagement and performance in biomechanics. Student interests were incorporated into biomechanics lectures to engage underrepresented students in STEM. One cohort received interest-tailored lectures (intervention group) and the other cohort received generic lectures of the same content (control group). Key findings from this study are as followed:

- Interest-tailored lectures increased student engagement when compared to generic lectures.
- Students that received interest-tailored lectures scored 5% higher in student performance, but the increase was not significant. However, a 5% increase can be meaningful to grade outcome and future student motivation towards STEM.
- Students rated engagement in interest-tailored lectures similar to enjoyment in hands-on activities. Rated engagement in generic lectures was lower than enjoyment in hands-on activities. Interest-tailored lectures can boost student engagement to the level of hands-on activities.
- Students rated laboratory tours highest in enjoyment when compared to engagement scores for hands-on activities or either lecture type (interest-tailored or generic). Thus, students should be exposed to real-world STEM outside the classroom.

Utilizing student interests in course content is a promising pedagogical technique to engage underrepresented student in STEM. Future research should explore this pedagogical technique on a larger scale and across education levels.

Engaging underrepresented students in STEM is essential to grow diversity in the STEM fields. This can help facilitate the needed diversity in the safety field. Incorporating a variety of perspectives is imperative to designing engineering solutions that fit our diverse population. If all individuals are not considered in our designs, the underrepresented individuals may be at risk for adverse outcomes.

Appendix A: Background

Appendix A.1 Nomenclature

The following nomenclature was used to consolidate terminology in the literature. The terminology our nomenclature encompasses is outline below.

Appendix A.1.1 Setting

Domestic: domestic, non-occupational, home, home/farm.

Occupational: occupational, work.

Appendix A.1.2 Ladder type

Straight: straight, straight tilting, single, single-leg, portable single-leg ladder, extension, inclined.

Stepladder: stepladder, A-frame, step or trestle ladder.

Fixed: fixed, derrick/tower, scaffold end frame, dock, deck, ship tank.

Other: multi-purpose ladder, platform, rolling/wheeled, trestle, job-made ladder, ladder substitute (e.g. chair), aerial, fruit picker, storeroom.

Appendix A.1.3 Ladder use activity

Maintenance/repair or painting: maintenance, repairing, roof repairs, painting, installing electrical cable, electrical work, plant or building maintenance/repair, vehicle or equipment maintenance/repair, hanging/repositioning, changing or replacing a light bulb.

Gutter cleaning: gutter cleaning.

Getting an object from the attic: getting an object from attic, retrieving items from a ceiling space.

Garden/yard pruning: pruning, cutting branches, tree work.

Decorating: decorating, decorating a Christmas tree.

Cleaning house/windows: cleaning house, cleaning boat, cleaning windows, washing a caravan, cleaning/washing.

Construction: building construction, equipment construction and installation, welding/cutting, welding, activities associated with concerting.

Production and transport: production and operations, production and transport, unloading a truck handling supplied loads, carrying/lifting/operation tool.

Removing snow from the roof: removing snow from roof.

Other ladder use activities reported in the literature that were not mentioned in the background were removing animal from a roof, climbing to the roof, stocking or retrieving item from shelf, reaching/pushing/pulling and inspecting.

Appendix A.1.4 Action at time of fall

Standing/working: standing, working from ladder, reaching too far sideways while standing, standing or sitting.

Ascent: ascent, ascending, climbing up, ingress.

Descent: descent, descending, climbing down, egress.

Appendix A.1.5 Cause of fall

To better assess the cause of the ladder fall. Nomenclate was specific in regards to the ladder falling (tipped or slipped) or the climber falling (slip, misstep or lost balance) when possible.

Ladder tipped: ladder tipped, twisting at ladder top, sliding/tipping at ladder top, slipping at top, twisting, ladder falling, lateral sliding at top.

Ladder slipped: ladder slipped, ladder base slipped, sliding at the base, sliding at bottom.

Ladder tipped or slipped: ladder instability, ladder moved, ladder movement.

Climber slip: climber slip, slip, foot slip.

Climber misstep: climber misstep, misstep, foot miss.

Climber lost balance: loss of balance, lost balance, swaying.

Climber slip/misstep or lost balance: climber slip/misstep, foot slip/misstep, person stumbling or misstep, slip or lost balance.

Overreaching: overreaching, overextension, overbalance, overreached.

Transitioning: transitioning, transitioning onto/from ladder, stepping on/off ladder, transition, climber misstep of bottom rung.

External force or object interference: external force, object interference, thrown off ladder, tool/machine slipped, struck by or attempting to catch/avoid falling object, applying excessive force, struck by/knocked, external ladder cause, climber bumped head.

Improper setup/use: improper setup, improper use, leaning stepladder against structure, used the wrong side for access /work, standing on the top rung.

Unstable surface: surface collapsed/broke, placed on scaffold, surface moved.

Mechanical failure: mechanical failure, defective ladder, malfunction, ladder broke.

Hand grip failed: hand grip failed, hands slipped, lost handgrip.

Electric shock: electric shock, electrocution.

Pre-existing condition: pre-existing condition, vertigo, cardiovascular accident.

Appendix A.1.6 Injury

Fracture: fracture, chip, fractured neck, fractured chest, multiple fractures.

Sprain/strain: sprain/strain.

Lacerations/avulsion: lacerations, avulsion, cuts, punctures, cut/puncture.

Dislocation: dislocation, luxation.

Head injury: multi-trauma including head injury, concussion, concussion/other injury, brain injury, skull fracture, intracerebral hemorrhage, subdural/epidural hematoma, neck fracture.

Superficial injury: superficial injury, wound, contusion, bruise, contusions/abrasions, tissue wounds, bruise/impact, scratches.

Other injuries: other, injury to nerves, blood vessels, internal organs.

Other ladder injuries reported in the literature that were not mentioned in the background were multi-trauma with excluding injury, multi-trauma with spinal injury, body system/multiple injuries and asphyxia.

Appendix A.1.7 Injury location

Upper extremities: finger, hand, wrist, arm, forearm, elbow, shoulder.

Lower extremities: toe, foot, ankle, leg, knee, hip.

Head: head, head/neck, head/face, face, brain, neck.

Trunk: thorax, abdomen, chest, pelvis, thorax, lower trunk, upper trunk, spine, back.

Appendix A.2 Ladder Climbing Patterns

The conference proceeding below was peer-reviewed and published in the Proceedings of the Human Factors and Ergonomics Society Annual Meeting [190]. The proceeding provides details on ladder climbing patterns and their relationship with ladder fall severity.

Appendix A.2.1 Effects of ladder climbing patterns on fall severity

Abstract: A fall from a ladder is the most common cause of a fatal fall injury to a lower level. Current guidelines recommend proper ladder climbing to avoid a ladder fall, but there is a lack of understanding on safe ladder climbing biomechanics. The purpose of this study was to investigate the effects of different temporal (2-beat, 4-beat) and coordination (lateral, diagonal) ladder climbing patterns on fall severity. In this study, fall severity is quantified as the peak weight supported by a safety harness (normalized to body weight) after a climbing perturbation. A greater harness force is associated with a greater probability of a falling event resulting into a fall. The airborne times of the hand and foot for each climbing pattern were investigated to better understanding differences between climbing patterns. This study did not find climbing patterns to affect fall severity. Thus, the events that occur after a ladder climbing perturbation may be more critical to consider when investigating ladder fall severity. Hand and foot airborne times varied by climbing pattern. Specifically, hand airborne times for the lateral coordination pattern were 19%

longer than those of the diagonal coordination pattern. Foot airborne times of the 2-beat temporal pattern were 15% longer than those of the 4-beat temporal pattern. Increased airborne times may be indicative of overlapping regions and resources competition in the primary cortex.

INTRODUCTION

Fall injuries are a leading cause of disabling injuries [1]. The majority of fatal fall injuries are a result of a person falling to a lower level (i.e. fall from a ladder) [24]. The most common cause for a fatal fall to a lower level is from a ladder [26]. The high number of ladder fall injuries shows a need to improve ladder climbing practices and guidelines.

Current ladder climbing guidelines stress the avoidance of improper climbing movements [191], but there is a lack of understanding on climbing biomechanics that are safer. Previous literature that investigated ladder climbing biomechanics, determined two different temporal and coordination climbing patterns [73-75]. The two temporal patterns observed were 2-beat (upper and lower limb moving in unison) and 4-beat (movement of each limb is staggered) [73, 74]. The two coordination patterns observed of the limbs with overlapping airborne phases were lateral (ipsilateral limbs moving together) and diagonal (contralateral limbs moving together). Interestingly, some individuals have been instructed to climb with the lateral coordination pattern for safety reasons [75], even though the relationship between ladder fall risk and climbing patterns has not been reported. Literature has reported 2-beat and lateral climbing to be the most common climbing patterns during ladder ascent and descent, attributing these patterns to enhanced stability [73]. This belief of enhanced stability agrees with literature reporting greater variability in climbing cycle (i.e. time from right foot contact to sequential right foot contact) for 4-beat, diagonal climbing [74], and the likelihood of greater climbing variability leading to a climbing misstep [79]. A lack of empirical data exists to confirm the relationship between climbing patterns and fall risk.

An important characteristic of ladder climbing to consider is the airborne phase of each limb. The limbs are airborne for 25% to 38% of the climbing cycle [73-75]. Therefore, the airborne phase during ladder climbing should be of interest, similar to how the swing phase is of interest during gait [192]. Reducing the limb airborne time in favor of increasing the limb contact time is recommended for safer ladder climbing [191], and 4-beat climbing is associated with greater durations of three limbs in contact with the ladder [74]. Therefore, the limb airborne times are likely to vary by climbing pattern. Knowing the limb airborne times for each climbing pattern may assist in understanding the effects of climbing patterns on ladder fall risk.

The purpose of this study is to determine the effects of temporal and coordination climbing patterns on fall severity (i.e. a measure to assess fall risk) after a ladder climbing perturbation. The hand and foot airborne times for each climbing pattern were assessed to better understand how climbing patterns affect fall severity.

METHODS

Subjects

Thirty-five persons between the ages of 18 and 29 were recruited from the general public. Twenty-two males (23.8 ± 5.3 yrs., 80.6 ± 7.8 kg, 1.8 ± 0.1 m) and 13 females (25.5 ± 6.0 yrs., 63.3 ± 6.6 kg, 1.7 ± 0.1 m) participated in this study. Participants did not need ladder climbing experience to be eligible for this study. Participants were excluded if they had any musculoskeletal disorders, previous shoulder dislocations, osteoporosis/osteoarthritis, neurological/cognitive disorders, balance disorders or were pregnant. Informed consent and Institutional Review Board approval (Protocol Number: 11.366) was obtained at the University of Wisconsin-Milwaukee.

Experiment Design

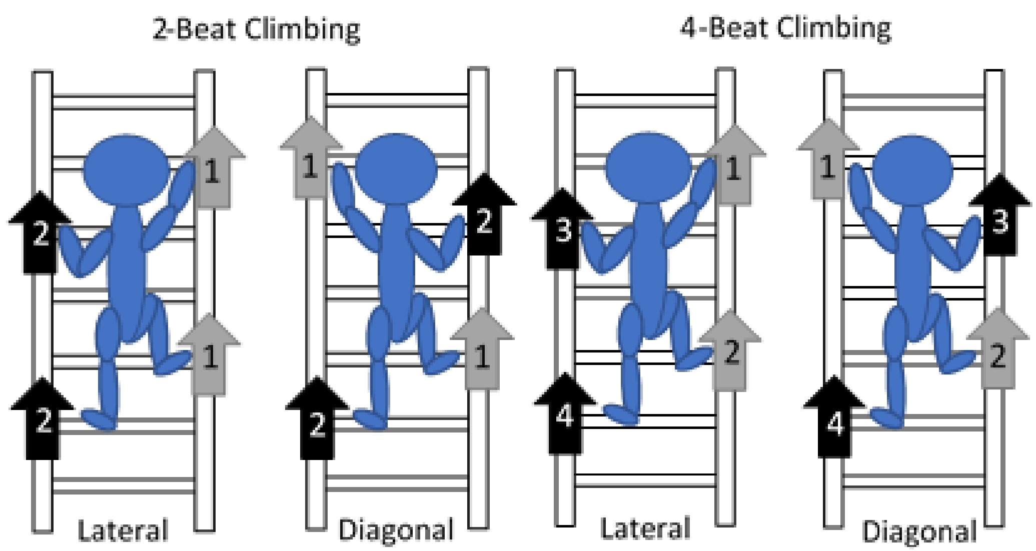
Prior to testing, anthropometric measures (i.e. height and weight) of the participants were taken and participants were equipped with standardized attire. Specifically, participants wore athletic attire, a standard work shoe with a raised heel, and shin guards to protect their shanks from hitting any ladder rungs. In addition, participants were equipped with 47 reflective markers across the head, torso, upper extremities, and lower extremities to measure ladder climbing motion (100 Hz). This study analyzed the motion of the markers placed on the anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), the third metacarpal (dorsum), the 1^{st} and 5^{th} metatarsal (dorsum), and the middle toe (middle dorsum and superior surface of the shoe).

Participants were asked to climb a 12-foot, custom, vertically fixed ladder 30 times at a comfortable but urgent pace to simulate the ladder climbing speed of a regular-to-busy work day. Participants were not instructed to climb the ladder with a specific climbing pattern and allowed to rest between climbs to limit fatigue. The diameter of the rungs were 31.75 mm (1.25 in) and the spacing between the rungs was 305 mm (12in), compliant with the Occupational Safety and Health Administration (OHSA) standards [92]. Participants experienced a ladder climbing perturbation during six of the climbs (three per climbing direction). The ladder climbing perturbation was simulated by releasing the fourth rung from the ladder. The release of the fourth rung was triggered when less than 5% of the climber's body weight remained on the previous rung. This allowed for a controlled perturbation across subjects and trials. In addition, the timing of this perturbation corresponds to the point in time when a person is most likely to slip off a ladder rung [82]. Three to six regular (unperturbed) climbs were performed prior to each perturbation trial to limit anticipation of the perturbation [80]. Participants acclimated to the ladder before recording baseline trials and prior to each perturbation. Participant safety was ensured with a safety harness, belayer, spotter, and impact mat. A load cell was equipped to the safety harness to measure the weight support by the harness (1000 Hz).

Data Analysis

Climbing patterns. Climbing patterns were assessed from the completed hand and foot movements prior to the initiation (rung release) of the perturbation trials. Climbing patterns are known to vary between climbing trials [73, 74]. Therefore, the movements during the step immediately prior to the perturbation are most likely to reflect the intended hand and foot movements during the step when the perturbation occurred.

The climbing patterns were calculated similar to previous literature. The temporal patterns that were characterized were 2-beat and 4-beat (Appendix Figure 1). Two-beat climbing is described as the hand and foot moving nearly simultaneous together, resulting in two phases of movements to move all limbs. Four-beat climbing is described by an interval of time between the movement start of one limb to the sequential movement start of the other limb, resulting in four phases of movements to move all limbs. This study calculated temporal patterns from the timing of hand and foot offsets/onsets. Specifically, 2-beat was classified as the hand offset and onset occurring within the offset and onset window of the foot movement. Otherwise, if either the hand offset or onset occurred outside the foot movement window, the temporal pattern was classified as 4-beat. The timing of hand movement relative to foot movement was selected because the hand airborne phase is typically shorter than the foot airborne phase [74]. In the few cases where the hand airborne phase was longer than the foot airborne phase, temporal pattern was reassessed. For these cases, 2-beat pattern was classified as the foot offset and onset occurring within the hand offset and onset window. Hand and foot offset/onset was based on exceeding/falling below a velocity threshold of the 3rd metacarpal and forefoot mid-point (i.e. the mid-point of the 1st and 5th metatarsal and middle toe markers) for the hand and foot, respectively. This velocity threshold was 10% of the peak velocity of the corresponding movement [82].



Appendix Figure 1: Ladder climbing patterns. The two left ladder climbers show 2-beat climbing for lateral (far left) and diagonal (middle left) coordination patterns. The two right climbers show 4-beat climbing for lateral (middle right) and diagonal (far right) coordination patterns. The color corresponding arrows represent the limbs with overlapping airborne times. The numbers, represent the order of limb offset.

The two coordination patterns were lateral and diagonal. These coordination patterns were based on the hand and foot that was in motion (i.e. the left or right limb) in the same overlapping window. Specifically, if the two unison/staggered movements were both on one side of the body, this coordination pattern was classified as lateral. If the opposite occurred (i.e. left and right moving limbs), this coordination pattern was classified as diagonal.

Hand and foot airborne times. The hand and foot airborne times were recorded between the offset and onset of each hand and foot movement to assist in characterizing climbing patterns. Trials were excluded if the climber had an irregular climbing pattern (12 trials) (i.e. skipping rungs during climbing, an extended pause between each limb movement, climbing with two hand movements per foot movement). Climbing patterns were visually confirmed from displacement and velocity profiles of the moving limbs.

Climbing speed. Climbing speed was assessed to quantify the effects of climbing pattern on hand and foot airborne times. The purpose of this analysis was to determine if increased airborne time was caused by a slower climbing speed of the climbing pattern. A faster climbing speed would be indicated by a greater velocity magnitude (in the positive direction for ascent and negative direction for descent). Climbing speed was determined as the vertical velocity of the mid-hip joint center (MidHJC) at the time of perturbation onset (rung release). Mid-hip joint centers were found using the ASIS and PSIS markers and Bell's method [143].

Fall severity. Fall severity was measured as the peak weight supported by the safety harness between perturbation onset and the end of the perturbation. A greater supported weight was associated with a greater probability of a falling event resulting in a fall. Harness force measures were normalized by body weight. Perturbation onset was the time that the rung was triggered to release. The end of the perturbation was the first harness force local maximum after a local minimum in the MidHJC's vertical displacement following perturbation onset [127].

Statistical Analysis

Four repeated-measures ANOVAs were performed. Independent variables for these ANOVA models were subject number (random), temporal pattern, coordination pattern, and the interaction between temporal and coordination pattern. The dependent variable of the first ANOVA was normalized harness force to test the effects of climbing patterns on fall risk. A square root transform was performed on normalized harness force to ensure a normality. The next two ANOVA models were run with hand and foot airborne times as the dependent variables to further characterize ladder climbing patterns. The last ANOVA was run with the vertical velocity of the MidHJC to validate the effects of climbing patterns on airborne times. A log transform was performed on vertical velocity of the MidHJC to ensure a normality. All analyses were run separately for ascent and descent.

RESULTS

During ascending climbs, the occurrence of 2-beat and 4-beat, and lateral and diagonal patterns were similar (bolded percentages in the not shaded region in Appendix Table 1). Specifically, 2-beat (51.3%) occurred slightly more than 4-beat (48.8%), and diagonal (53.8%) occurred slightly more than lateral (46.3%). Of the combined ascending patterns, 4-beat, diagonal

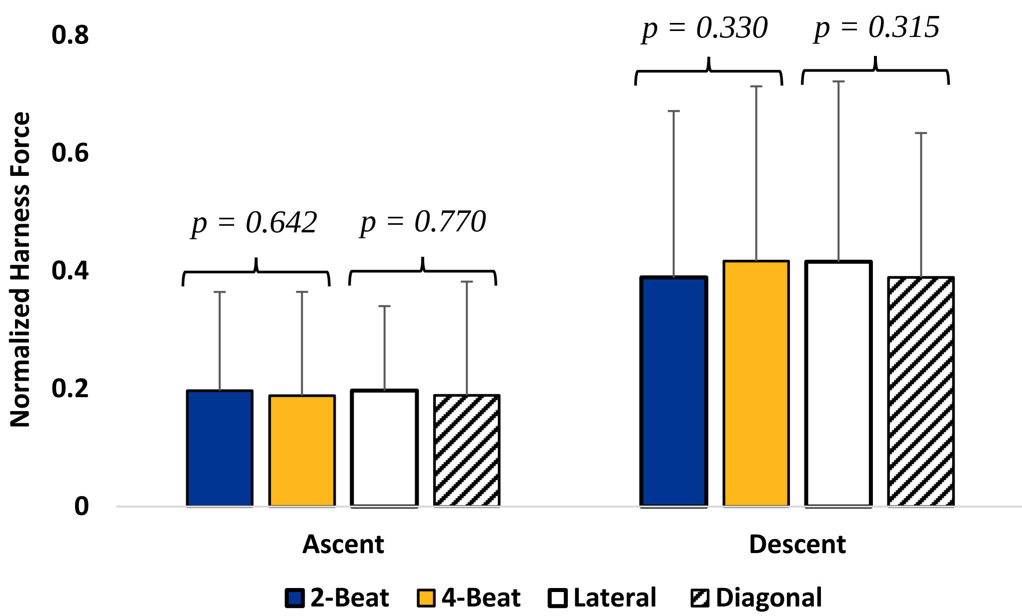
(31.3%) occurred the most and 4-beat, lateral occurred the least (17.5%) (not bold percentages in the not shaded region of Appendix Table 1).

During descent, 4-beat climbing (73.2%) occurred more than 2-beat climbing (26.8%), and lateral climbing (76.1%) occurred more than diagonal climbing (23.9) (bolded percentages in the shaded region of Appendix Table 1). Of the combined descending patterns, 4-beat, lateral (56.3%) occurred the most and 2-beat, diagonal (7%) occurred the least (not bold percentages in the shaded region of Appendix Table 1).

Appendix Table 1: Climbing pattern distribution. Percent distribution during ascent (not shaded region) and descent (shaded region).

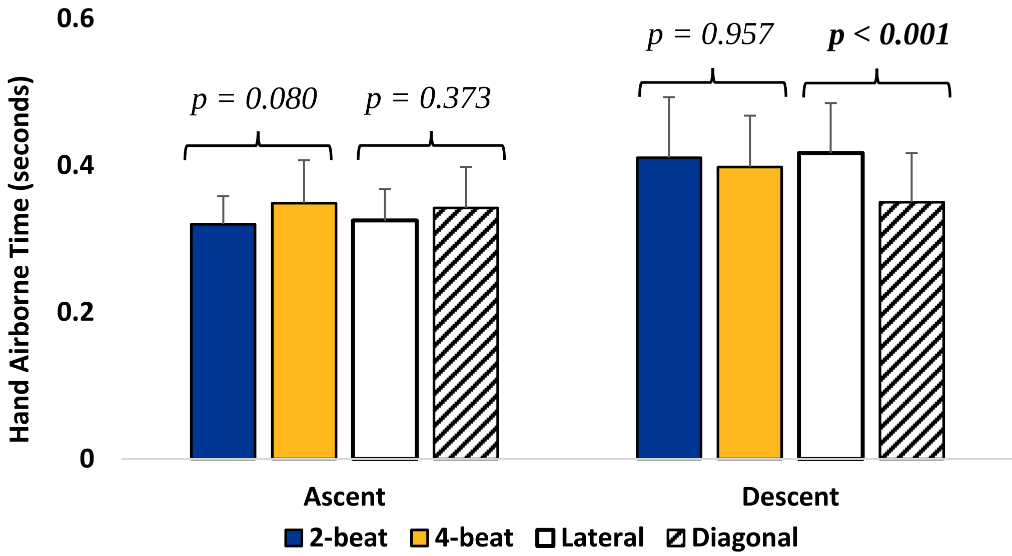
	Ascent	Descent	Ascent	Descent	Ascent	Descent
	Lateral		*Diagonal*		***Sum***	
2-Beat	28.8	19.7	22.5	7.0	**51.3**	**26.8**
4-Beat	17.5	56.3	31.3	16.9	**48.8**	**73.2**
Sum	**46.3**	**76.1**	**53.8**	**23.9**		

The average (standard deviation) normalized harness force after ascending and descending perturbations was 0.19 (0.17) and 0.41 (0.29), respectively. Normalized harness force did not vary across temporal (p = 0.642; F = 0.22) or coordination (p = 0.770; F = 0.09) climbing patterns for ascent. Similar, normalized harness force did not vary across temporal (p = 0.330; F = 0.97) or coordination (p = 0.315; F = 1.03) climbing patterns for descent (Appendix Figure 2). In addition, the temporal and coordination pattern interaction did not vary by normalized harness force for ascent (p = 0.910; F = 0.01) or descent (p = 0.748; F = 0.10).

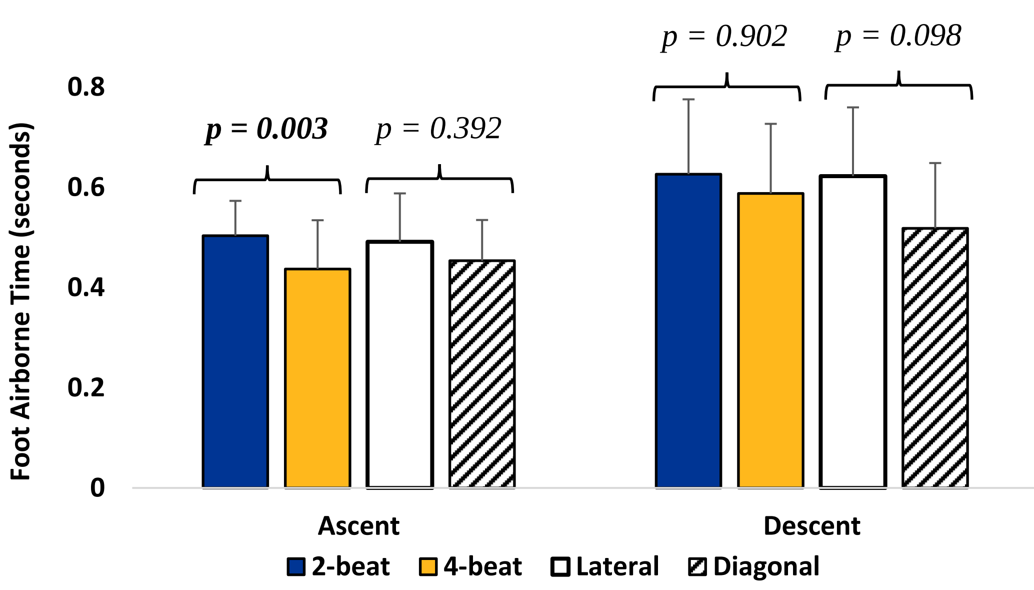


Appendix Figure 2: Normalized harness force across climbing patterns for ascent and descent. Error bars denote standard deviations. Bold *p*-values denote statistical significance.

Average (standard deviation) hand airborne times were 0.33 (0.05) seconds and 0.40 (0.07) seconds for ascent and descent, respectively. Average (standard deviation) foot airborne times were 0.47 (0.09) seconds and 0.60 (0.14) seconds for ascent and descent, respectively. Hand airborne time was unaffected by the temporal (p = 0.080; F = 3.14), coordination (p = 0.373; F = 0.80) and interaction (p = 0.973; F < 0.01) climbing patterns during ascent. Hand airborne time was affected by coordination (p < 0.001; F=20.48), but not affected by temporal (p = 0.957; F < 0.01) and interaction (p = 0.372; F = 0.81) climbing patterns during descent (Appendix Figure 3). Specifically, the lateral coordination hand airborne times were 19% longer than the diagonal coordination hand airborne times. Foot airborne time was affected by temporal (p = 0.003; F = 9.52), but not affected by coordination (p = 0.392; F = 0.74) and interaction (p = 0.507; F = 0.45) climbing patterns during ascent. Two-beat ascent resulted in foot airborne times 15% longer than 4-beat foot airborne times. Foot airborne time was not affected by temporal (p = 0.902; F = 0.02), coordination (p = 0.098; F = 2.86), and interaction (p = 0.998; F < 0.01) climbing patterns during descent (Appendix Figure 4).



Appendix Figure 3: Hand airborne time across climbing pattern for ascent and descent. Error bars denote standard deviations. Bold *p*-values denote statistical significance.



Appendix Figure 4: Foot airborne time across climbing pattern for ascent and descent. Error bars denote standard deviations. Bold *p*-values denote statistical significance.

The vertical velocity of the MidHJC was not affected by temporal (p = 0.514; F = 0.43), coordination (p = 0.505; F = 0.45), and interaction (p = 0.699; F = 0.15) climbing patterns, during ascent. Similar, the vertical velocity of the MidHJC was not affected by temporal (p = 0.715; F = 0.14), coordination (p = 0.867; F = 0.03), and interaction (p = 0.969; F < 0.01) climbing patterns, during descent.

DISCUSSION

Despite previous suggestions that certain ladder climbing patterns are safer, this study does not suggest a specific climbing pattern to improve recovery with a ladder after a perturbation. The measure of fall severity (harness force) used in this study was similar across temporal and coordination patterns. One explanation for these results may be that the recovery response of the body after the climbing perturbation may be a more critical factor of ladder fall severity than the movement patterns prior to a perturbation. This is consistent by previous ladder fall research that found different hand and foot placements after a ladder perturbation to affect fall severity [152]

Each climbing patterns was used with similar frequency during ladder ascent but 4-beat and lateral patterns were used more frequently during ladder descent. Climbing patterns did not affect harness force. Hand airborne times were smaller for the diagonal climbing pattern than lateral climbing pattern during descent. Foot airborne times were smaller for the 4-beat climbing pattern than 2-beat climbing pattern during ascent.

Overall, there does not seem to be a preferred climbing pattern during ladder ascent, agreeing with findings by McIntrye (1983). During ladder descent, 4-beat, lateral climbing was used the most, partially contradicting findings by Hammer and Schmalz (1992), who reported 2-

beat, lateral climbing to be used the most during descent. Differences on frequency of climbing patterns between the present study and earlier research may be due to differences in the analytical methods of determining climbing patterns. This study defined the 2-beat temporal pattern as the hand movement phase occurring within the foot movement phase (or vice versa). Other studies did not describe their methodology for defining these patterns [73-75].

The effects of climbing patterns on airborne times appears to be independent of the effect of climbing patterns on the vertical velocity of the MidHJC. Airborne times were dependent on climbing pattern but were not influenced by climbing speed. This indicates that the increase in airborne times is not due to a slower climbing speed per corresponding climbing pattern, but is a characteristic of the climbing pattern movement. Hand airborne times were less than the foot airborne times, agreeing with previous literature [74]. The faster movement times of the hand for diagonal climbing during descent and the foot for 4-beat climbing during ascent may be explained neurologically.

The increase in hand airborne times for the diagonal climbing pattern during descent may be explained by motor control theory. The diagonal coordination pattern likely recruits motor commands from the left and right hemispheres of the motor cortex for the respective hand and foot movements simultaneously. The lateral coordination pattern, however, is recruiting motor commands from mainly one hemisphere at one time. Previous literature has shown task performance and activity in the cortex to reduce during a dual vision and motor task when recruited primary cortex regions were overlapping [193]. Therefore, the speed of the hand during lateral climbing may have reduced due to overlapping recruitment in the primary cortex. Four-beat climbing during ascent may have resulted in faster foot movements due to increase time between limb movements. This time increase between movement tasks, results in less task overlap, lowering competition of motor processing resources [102].

There are certain limitations with this study that should be acknowledged. Climbing pattern was not controlled for, but observed. Climbing patterns are known to change within and between climbs [73, 74]. This analysis assumes the climbing patterns performed by the hand and foot movements prior to the perturbation reflected the intended climbing patterns of the hand and foot during the perturbation. Future studies should consider controlling ladder climbing patterns to better assess causality. Also, other methods to assess climbing coordination like wavelet coherence for coordination patterns [194] should be considered.

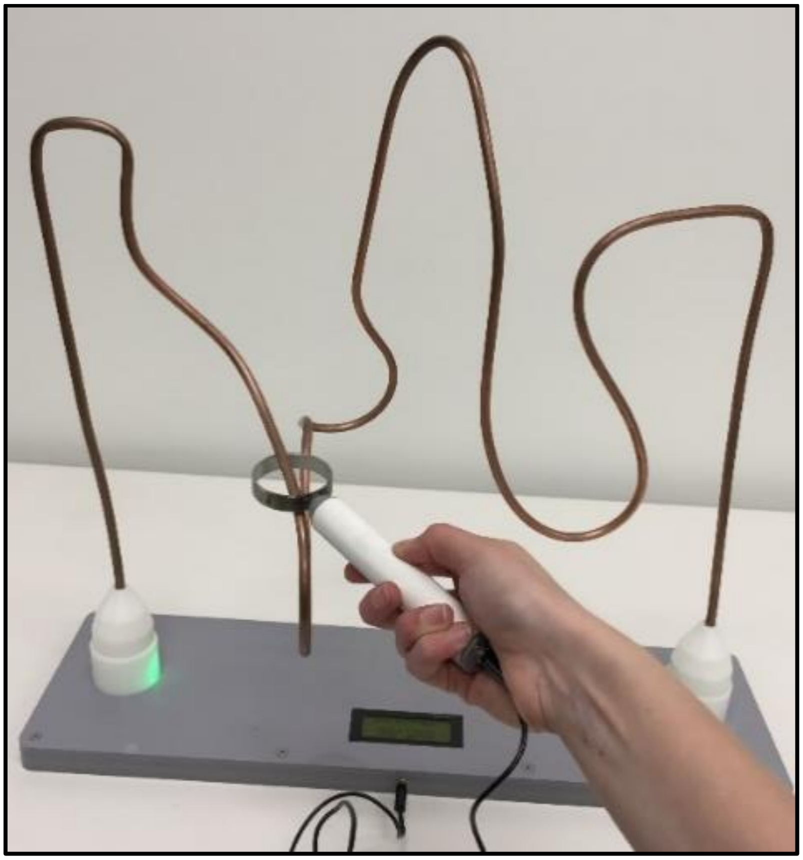
Overall, this study did not determine differences in ladder fall risk by climbing patterns prior to the perturbation. Thus, the biomechanical response after a perturbation may be more critical to consider when evaluating ladder fall risk. The differences in airborne times of the hand and foot by climbing patterns may be related to overlapping regions and resources competition in the primary cortex.

Appendix B: Characterizing User-specific Factors of Ladder Fall Risk

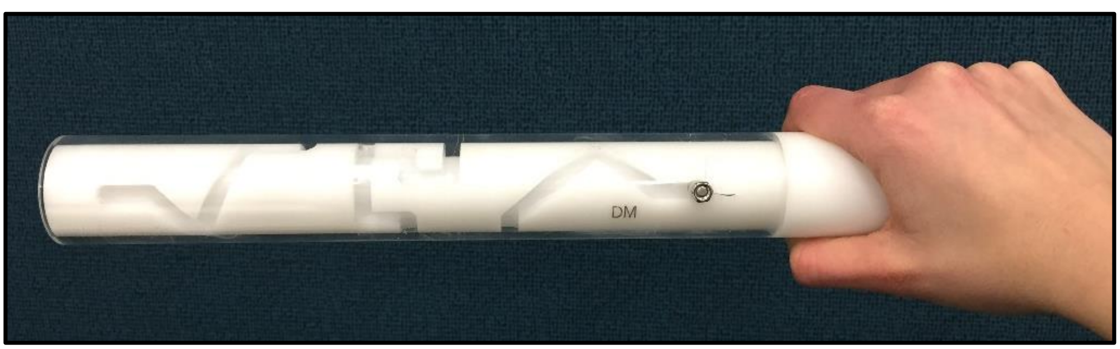
Appendix B.1 Methodology

Appendix B.1.1 Upper Limb Proprioception Physiological Assessment

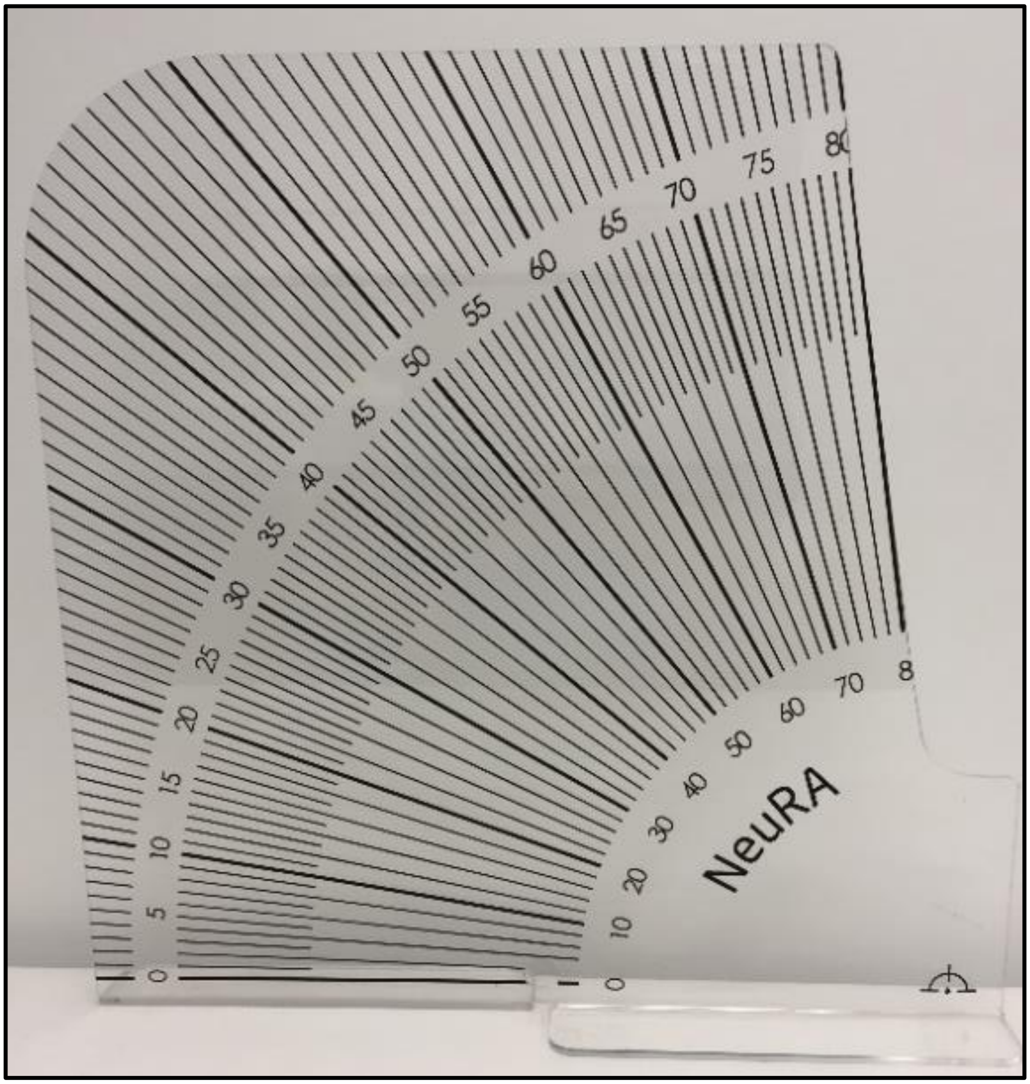
Appendix Figure 5: Finger tapping. Scoring is based on the total number of taps made by the pointer finger of the dominant hand in 10 seconds. A higher score is associated with better hand movement dexterity.



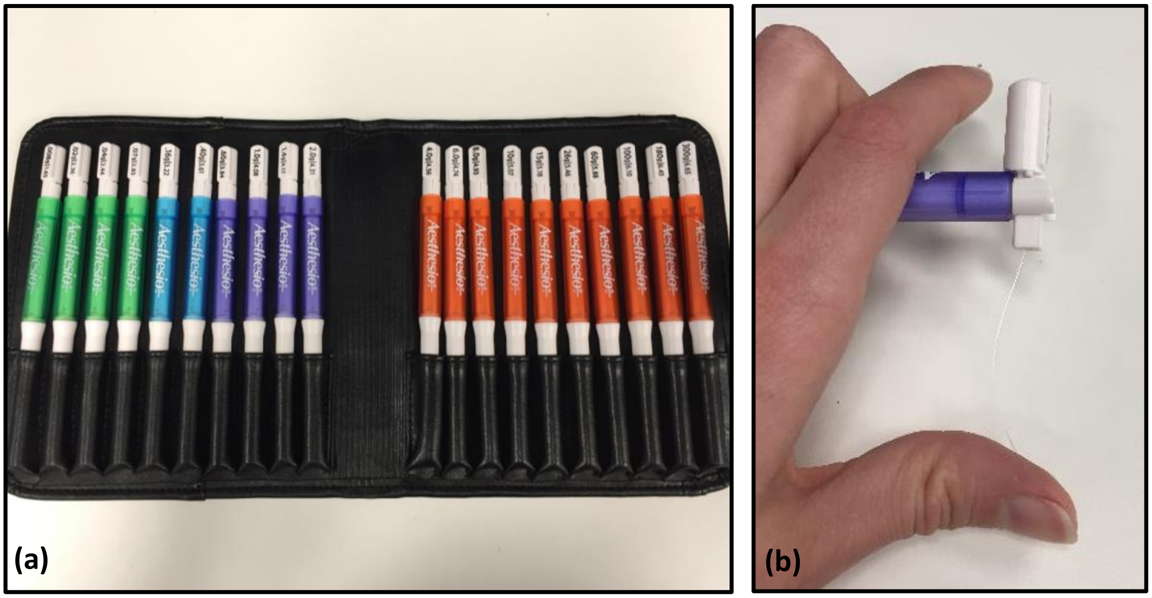
Appendix Figure 6: Loop & wire. Scoring is based on the total number of wire touches that occurred when the participant attempts to move the ring through the copper wire maze as fast and accurately as possible. A higher score is associated with reduced upper limb movement and dexterity.



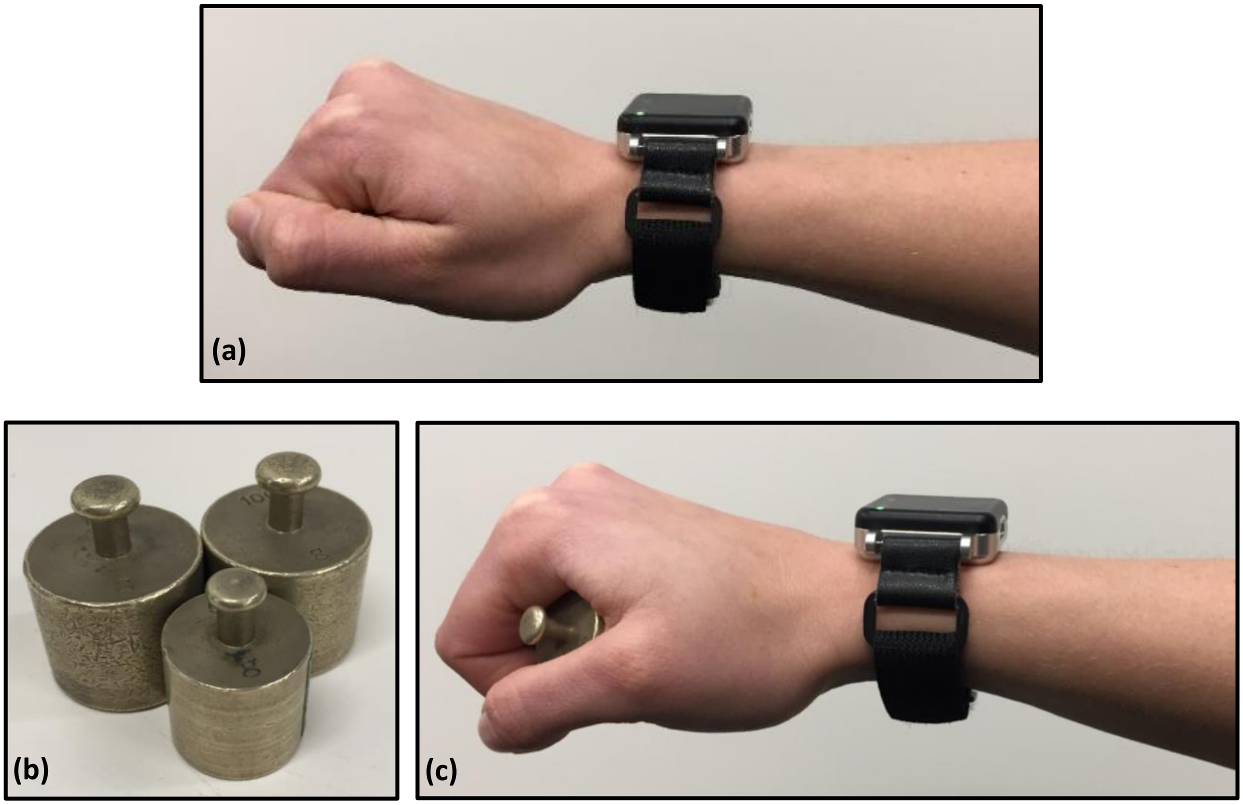
Appendix Figure 7: Bimanual pole test. Scoring is based on the time to move through the pole maze by pulling the inner and outer layers of the pole out and together. A higher score is associated with reduced bimanual coordination.



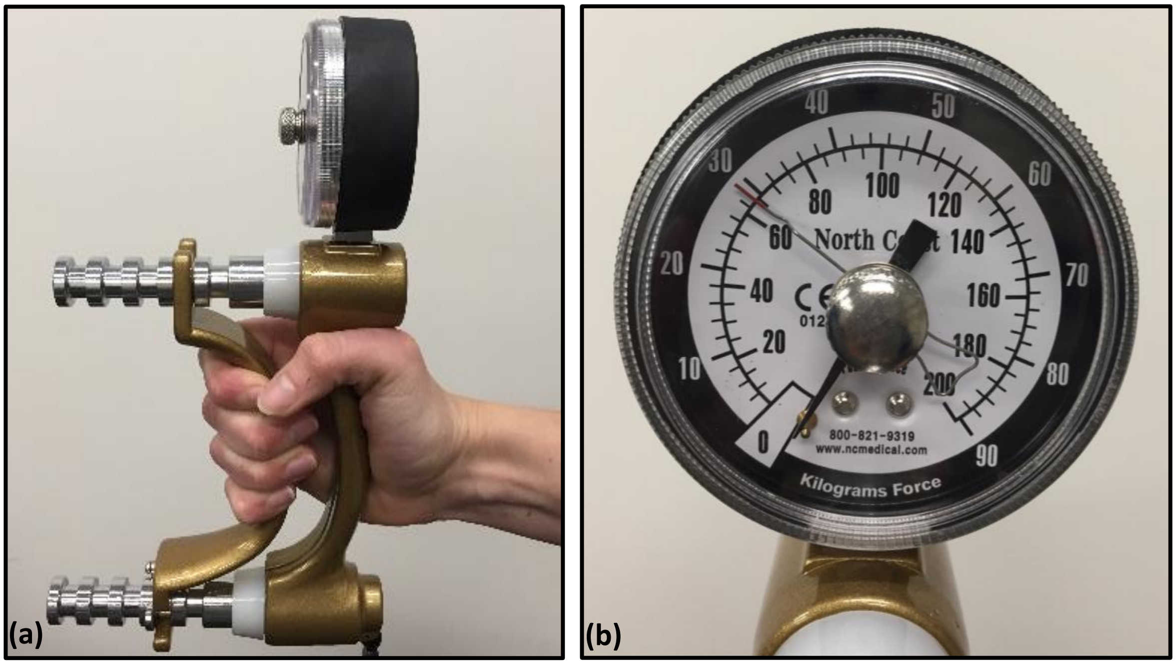
Appendix Figure 8: Elbow proprioception. The elbows were aligned at the point on the bottom right side of the board. Participants were blindfolded and a test administrator moved the pointer finger of the non-dominant hand to a position on the board. Participants were asked to match the finger of their dominant to the finger of their non-dominant hand while keeping their elbows fixed. Scoring is based on the average error in matching the pointer finger position of the dominant hand to the pointer finger of the non-dominant hand. A higher score was associated with reduced upper limb proprioception.



Appendix Figure 9: Tactile sensitivity. Scoring is based on the lightest force that can be sensed on the palm of the dominant hand by filaments of various diameters (a). The filaments were calibrated to buckle at a specific force (b). Participants were blindfolded for this test. A higher score is associated with a reduced tactile sensation in the hand.

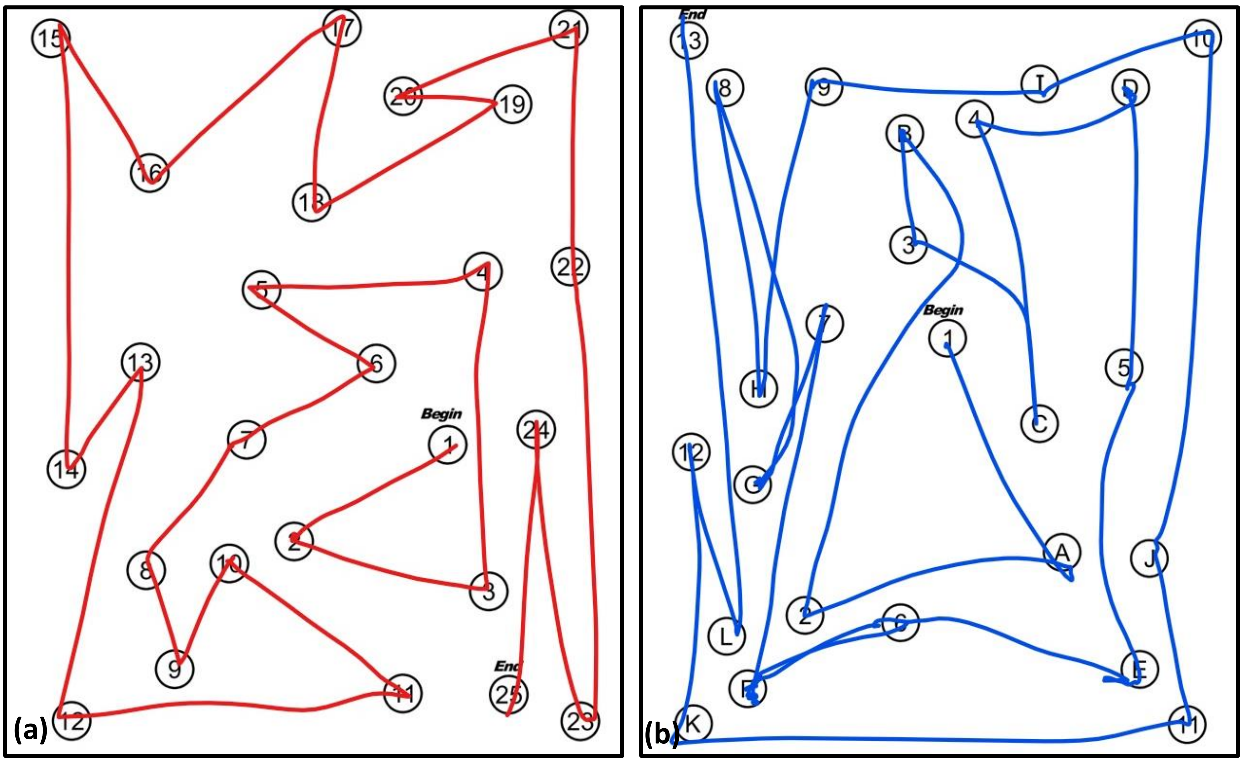


Appendix Figure 10: Arm stability. Scoring is based on the total path length traveled that was recorded from an IMU on the wrist when holding the outreached dominant arm as straight as possible for 30 seconds. Participants completed this task with a closed fist and eyes open (a) and with 250 grams (b) inside a closed fist with eyes closed (c). A higher score is associated with reduced arm stability.



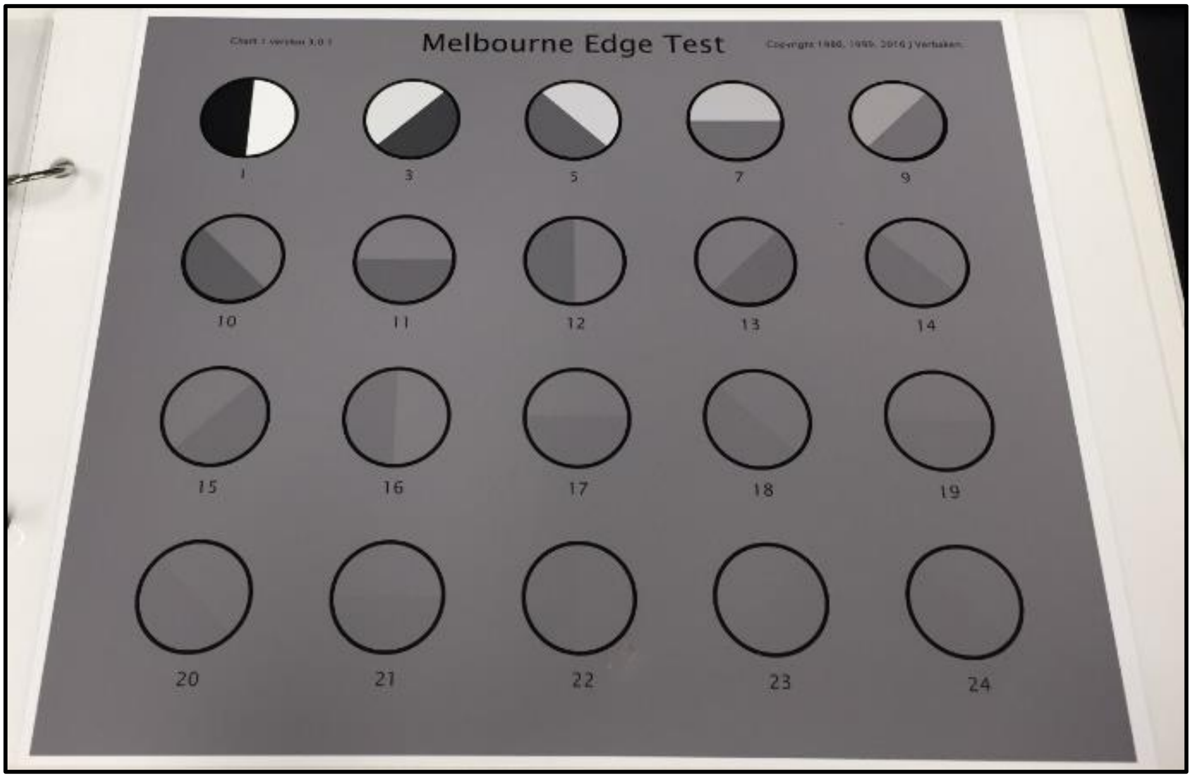
Appendix Figure 11: Grip strength. Scoring is based on the maximum force a participant can generated by squeezing two parallel bars with their hand (a). The ending location of the dial (red tip) reveal the exerted grip force (b). A higher score is associated with greater upper body strength.

Appendix B.1.2 Trails Making Test



Appendix Figure 12: Trails making test. Scoring for Trails A is based on time required to trace a line between numbers randomly distributed on a page in sequential order (a). Scoring for Trails B is based on time required to trace a line between numbers and letters randomly distributed on a page in number-letter sequential order (b). Scoring for Trails B-A is based on the difference in time to complete Trails A and Trails B. A higher score in Trails A is associated with reduced cognitive processing speed. A higher score in Trails B is associated with reduced cognitive processing speed and executive functioning. A higher score in Trails B-A is associated with reduced executive functioning.

Appendix B.1.3 Physiological Profile Assessment

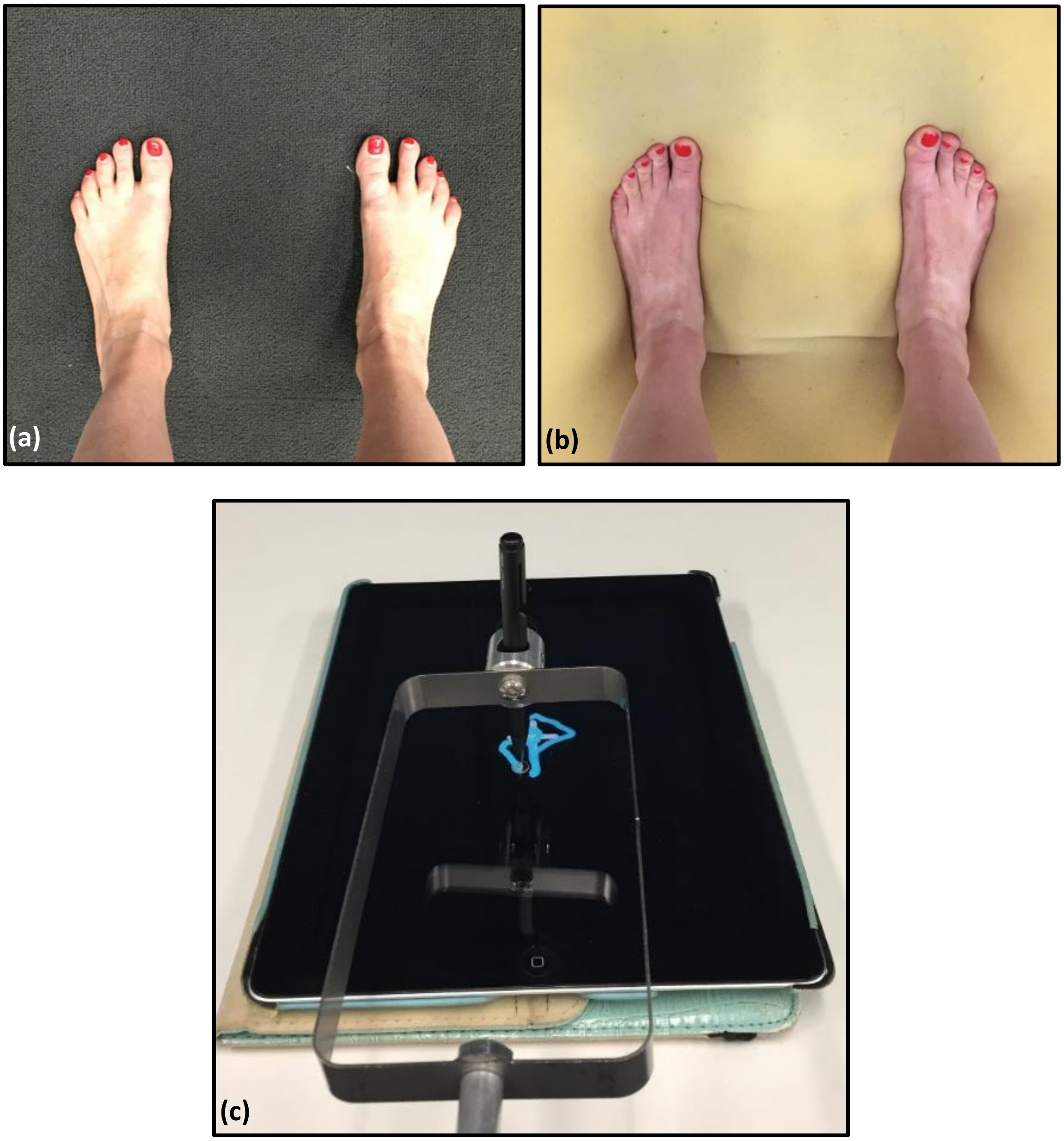


Appendix Figure 13: Edge contrast sensitivity. Scoring is from the Melbourne Edge Test (MET) – identifying the direction of the line created from two contrasting semi-circles. A higher score is associated with better contrast vision.

Appendix Figure 14: Hand reaction time. Scoring is based on the average time to left click on a computer mouse in response to the illumination of a red LED. A higher score is associated with a slower reaction time.

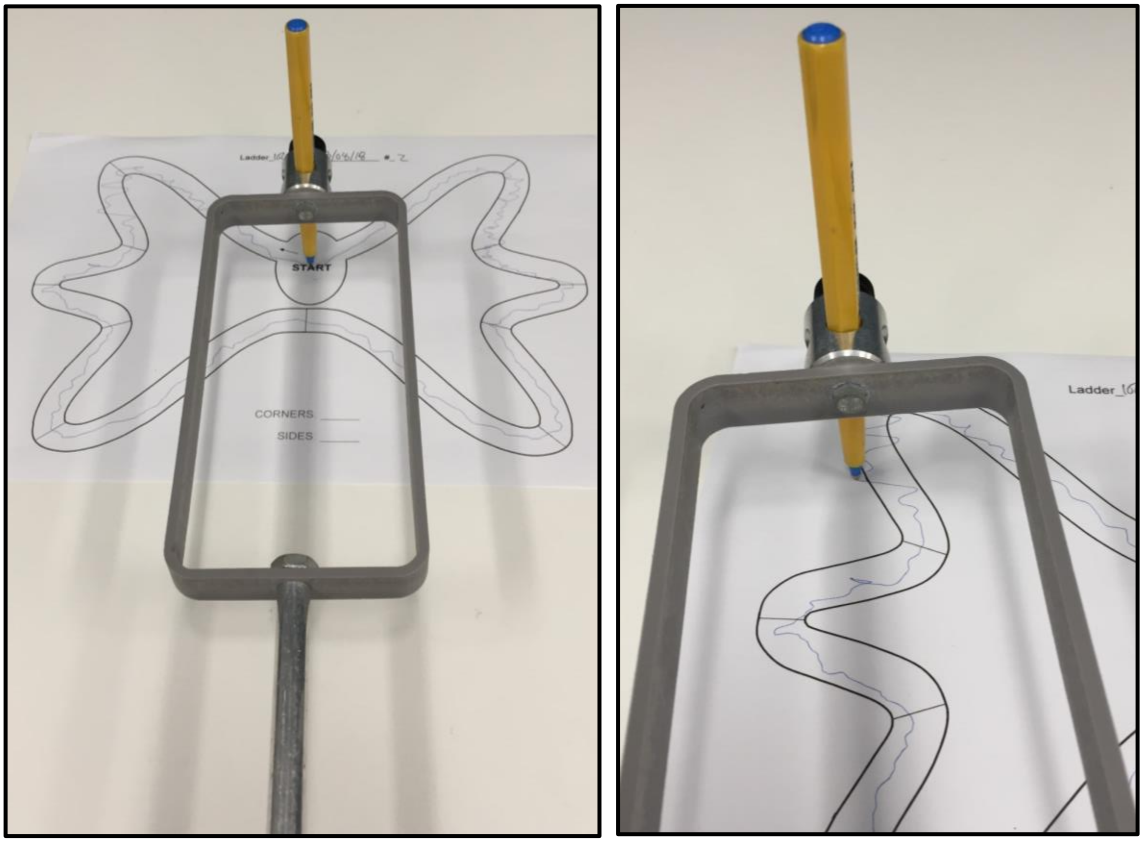
Appendix Figure 15: Lower limb proprioception. Participants sit in a high chair with their knees aligned at the top left side corner of the board. Participants close their eyes and attempt to touch the lateral side of the balls of their feet together. Scoring is based on the average error in matching the balls of the feet together. A higher score was associated with reduced lower limb proprioception.

Appendix Figure 16: Knee strength. Participants sit in a high chair. A strap in-line with a scale is secured just above the ankle of the dominant leg. Participants are encouranged to kick their dominant leg out to the best of their ability. The leg is secured, preventing movement, resulting in an isometric knee extension contraction. The extension force is recorded by the scale. Scoring is based on the maximum knee extension force. A higher score is associated with a greater knee strength.



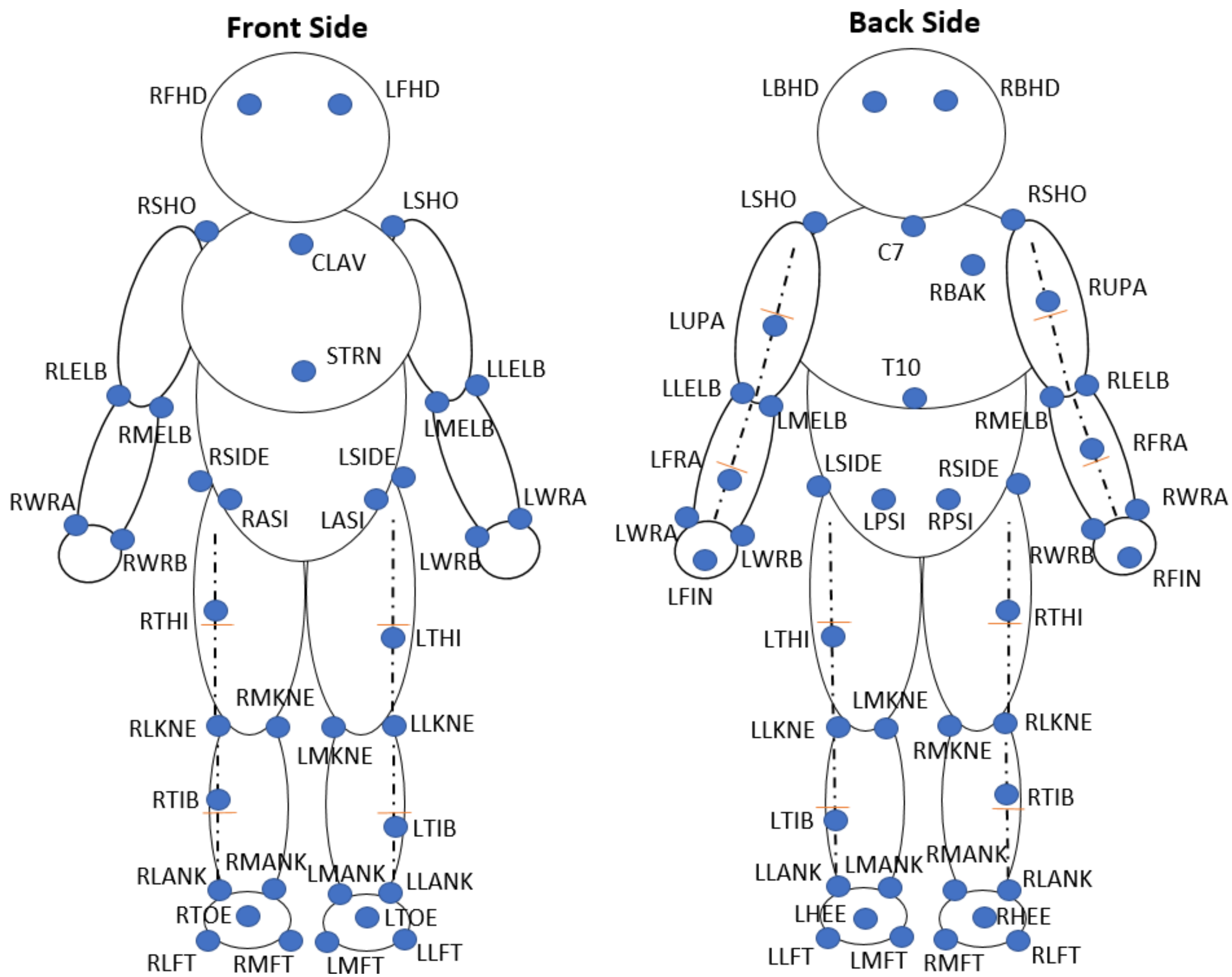
Appendix Figure 17: Sway. Standing balance was assessed with eyes open on the floor (a) and with eyes open on foam (b). Sway was measured from a swaymeter consisting of a stylus on an ipad that was connected to a rod parallel to the ground and attached to the posterior end of a belt on the participant (c). Participants were asked to stand quiet for 30 seconds while looking forward. Scoring was based on total path length traveled by the stylus. A higher score is associated with reduced balance.

Appendix B.1.4 Coordinated stability



Appendix Figure 18: Coordinated stability. Participants were wore a swaymeter consisting of a stylus connected to a rod parallel to the ground and attached to the anterior end of a belt on the participant. Participants were asked to guide the stylus through a track on a piece of paper without lifting up their feet (a). Everytime the stylus exited the track resulted in one error point. Everytime the stylus skiped a corner on the track resulted in 5 error points. Scoring was based on the total number of errors. A higher score is associated with reduced balance.

Appendix B.1.5 Climber marker template

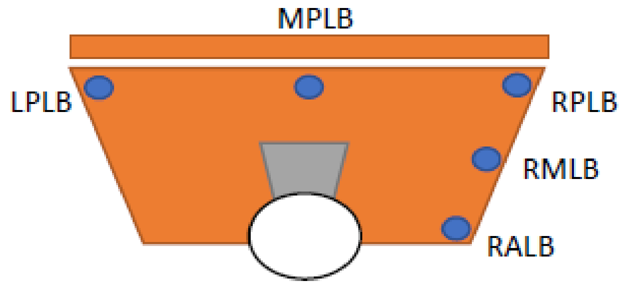


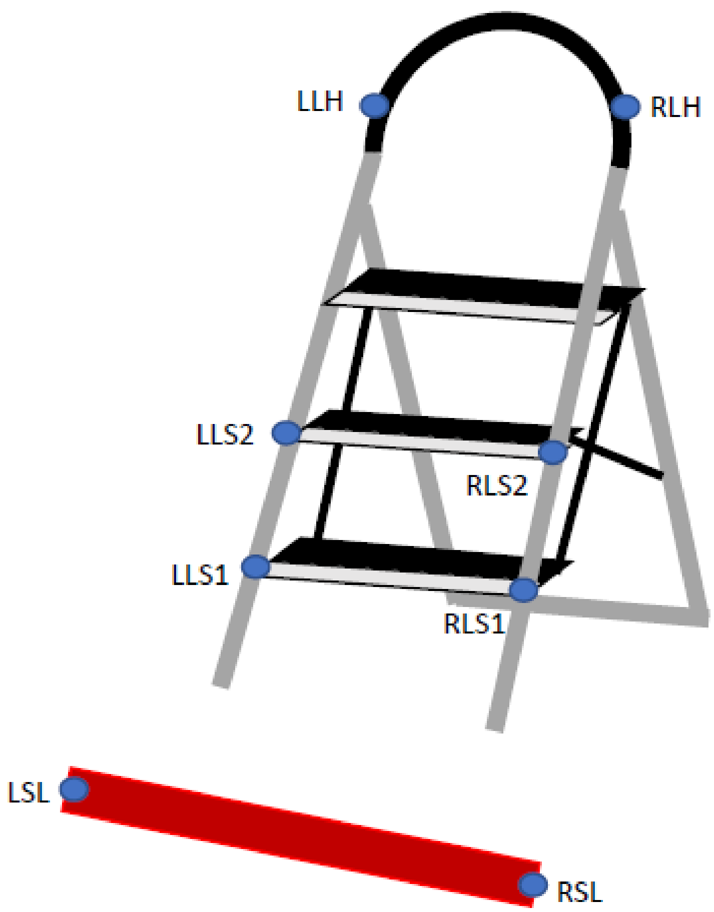
Appendix B.1.6 Abbreviations of climber markers

LFHD	Left front head
RFHD	Right font head
LBHD	Left back head
RBHD	Right back head
C7	7^{th} cervical vertebrae
T10	10^{th} thoracic vertebrae
CLAV	Clavicle
STRN	Sternum
RBAK	Right back
LSHO	Left shoulder
LUPA	Left upper arm
LLELB	Left lateral elbow
LMELB	Left medial elbow
LFRA	Left forearm
LWRA	Left wrist (thumb side)
LWRB	Left wrist (pinkie side)
LFIN	Left finger
RSHO	Right shoulder
RUPA	Right upper arm
RLELB	Right lateral elbow
RMELB	Right medial elbow
RFRA	Right forearm
RWRA	Right wrist (thumb side)
RWRB	Right wrist (pinkie side)
RFIN	Right finger
LASI	Left ASIS

RASI	Right ASIS
LPSI	Left PSIS
RPSI	Right PSIS
LSIDE	Left side
RSIDE	Right side
LTHI	Left thigh
LLKNE	Left lateral knee
LMKNE	Left medial knee
LTIB	Left tibia
LLANK	Left lateral ankle
LMANK	Left medial ankle
LHEE	Left heel
LLFT	Left lateral foot
LMFT	Left medial foot
LTOE	Left toe
RTHI	Right thigh
RLKNE	Right lateral knee
RMKNE	Right medial knee
RTIB	Right tibia
RLANK	Right lateral ankle
RMANK	Right medial ankle
RHEE	Right heel
RLFT	Right lateral foot
RMFT	Right medial foot
RTOE	Right toe

Appendix B.1.7 Ladder marker template

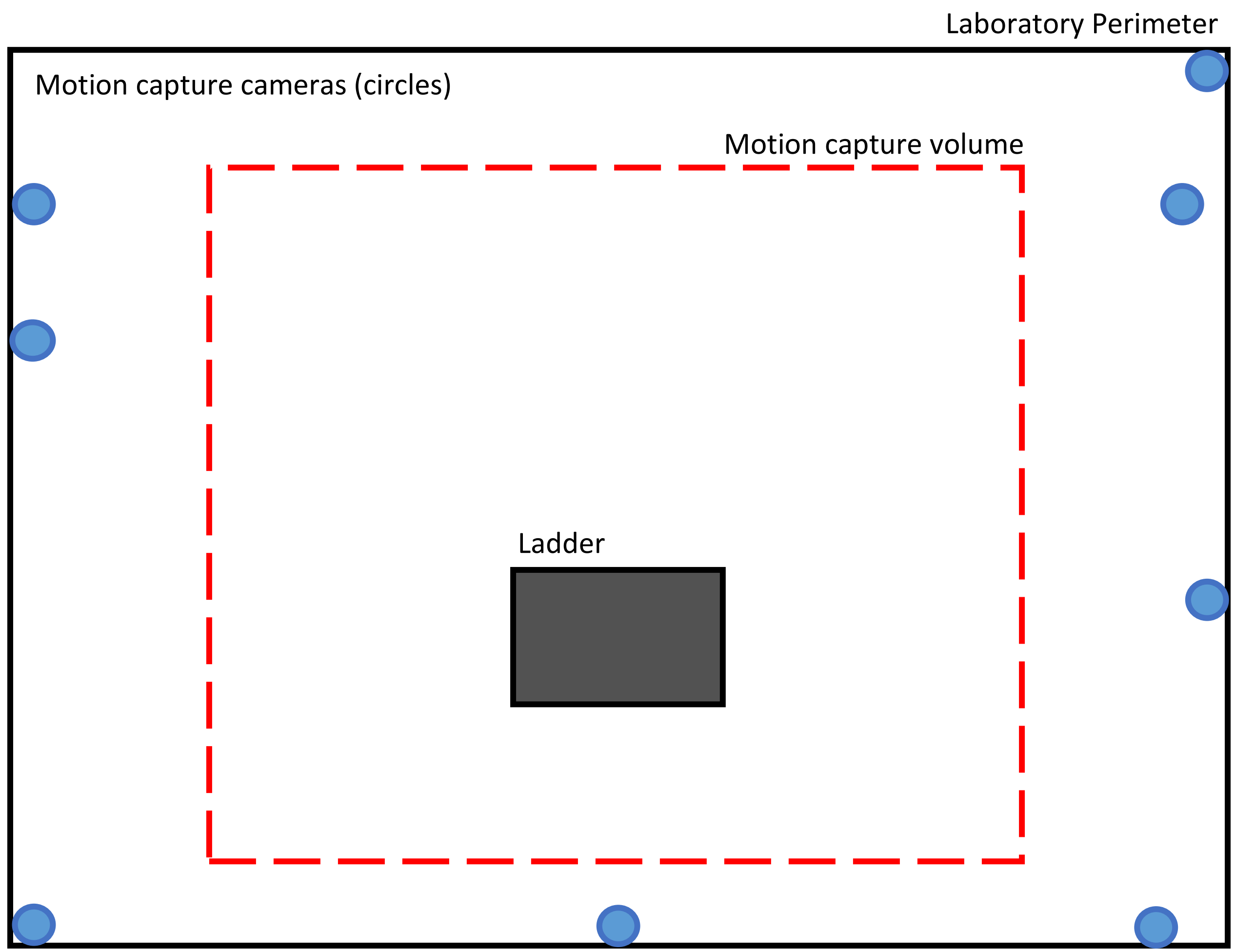




Appendix B.1.8 Abbreviations of ladder markers

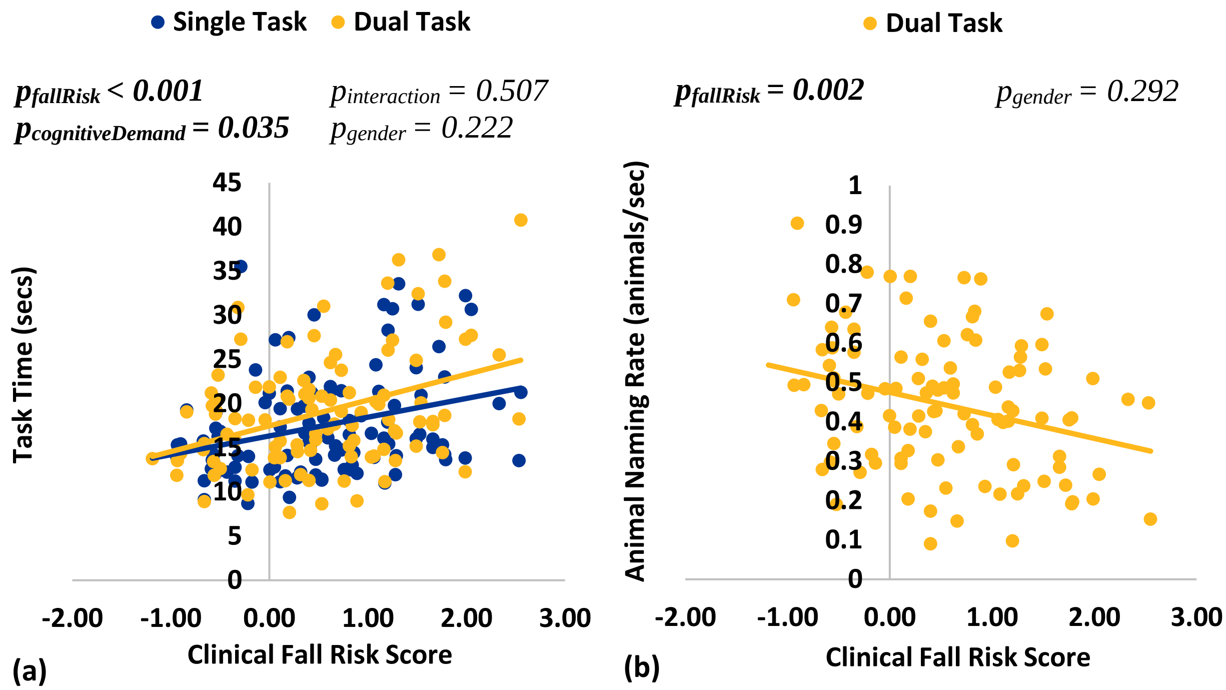
RSL	Right start line
LSL	Left start line
RLS1	Right ladder step 1
LLS1	Left ladder step 1
RLS2	Right ladder step 2
LLS2	Left ladder step 2
RLH	Right ladder handle
LLH	Left ladder handle
RPLB	Right posterior light bulb frame
RMLB	Right middle light bulb frame
RALB	Right anterior light bulb frame
MPLB	Middle posterior light bulb frame
LPLB	Left posterior light bulb frame
RSL	Right start line
LSL	Left start line
RLS1	Right ladder step 1
LLS1	Left ladder step 1
RLS2	Right ladder step 2

Appendix B.1.9 Motion capture volume with ladder and setup

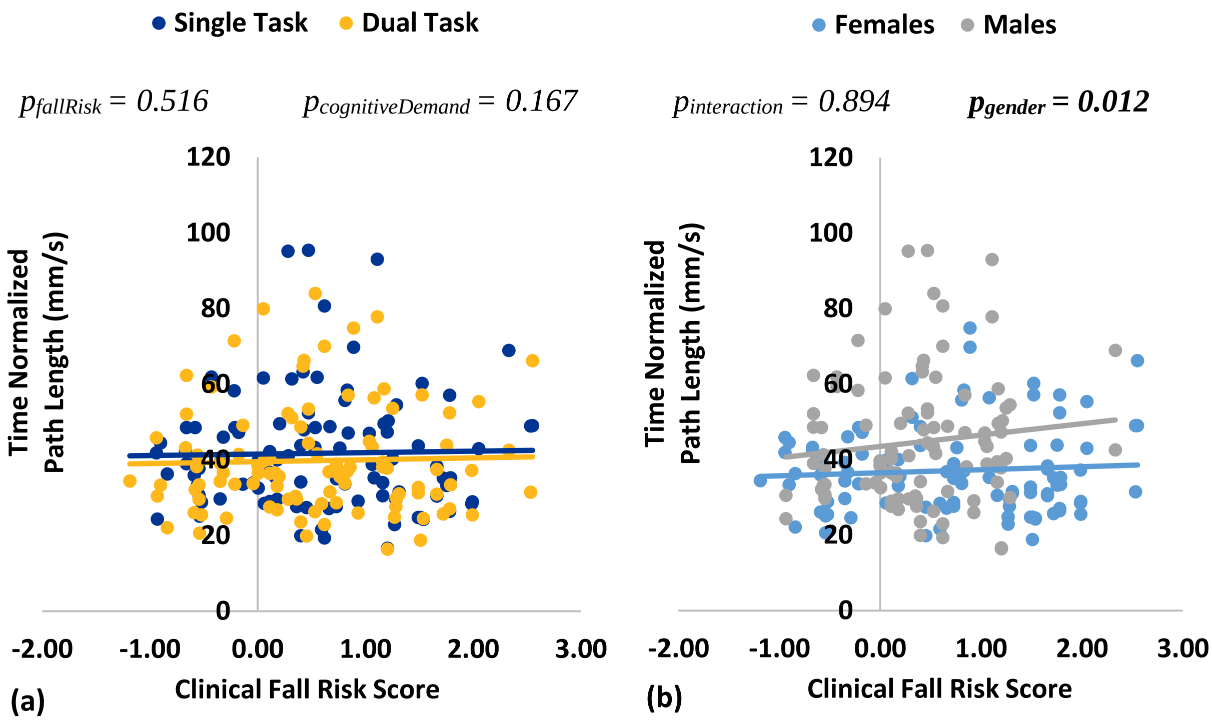


Appendix B.2 Supplementary Analyses

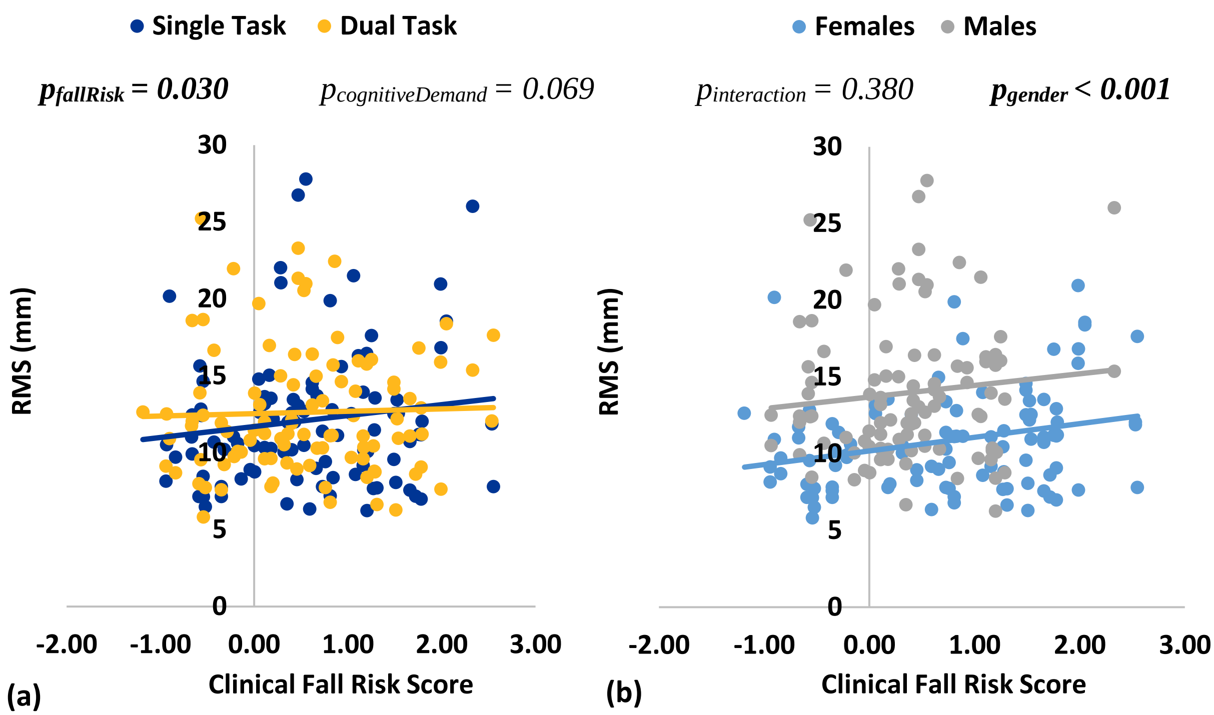
Appendix B.2.1 Task completion and standing stability metrics across clinical fall risk score



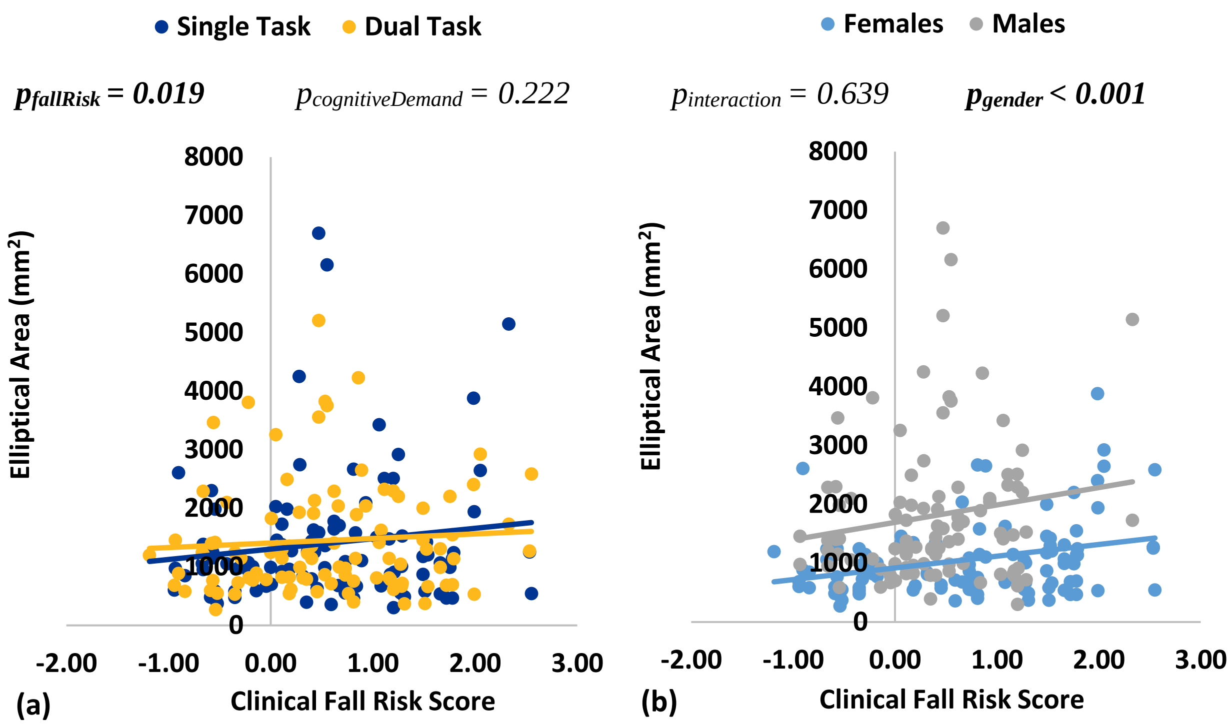
Appendix Figure 19: Task completion metric across fall risk. Task completion time (a) and animal naming rate (b) across a clincial fall risk metric. The clinical fall risk was calculated from the Physiological Profile Assessment (PPA) [113]. Task completion metrics are plotted for the single task (blue dots) and dual task (yellow dots) conditions. A repeated measures linear mixed model was performed with task completion metrics as the dependent variables and clincial fall risk score, cognitive demand, the interaction of fall risk score and cognitive demand, and gender (confounder) as the predictor variables. Bold *p*-values denote statistical significance.



Appendix Figure 20: Time normalized path length across fall risk. Time normalized path length of the center of pressure across a clinical fall risk score by cognitive demand (a) and gender (b). The clinical fall risk was calculated from the Physiological Profile Assessment (PPA) [113]. Time normalized path length is plotted for the single task (blue dots) and dual task (yellow dots) conditions and by females (light blue dots) and males (gray dots). A repeated measures linear mixed model was performed with time normalized path length as the dependent variable and clincial fall risk score, cognitive demand, the interaction of fall risk score and cognitive demand, and gender (confounder) as the predictor variables. Bold *p*-values denote statistical significance.



Appendix Figure 21: Root-mean-square across fall risk. Root-mean-square (RMS) of the center of pressure across a clinical fall risk score by cognitive demand (a) and gender (b). The clinical fall risk was calculated from the Physiological Profile Assessment (PPA) [113]. The RMS is plotted for the single task (blue dots) and dual task (yellow dots) conditions and by females (light blue dots) and males (gray dots). A repeated measures linear mixed model was performed with RMS as the dependent variable and clincial fall risk score, cognitive demand, the interaction of fall risk score and cognitive demand, and gender (confounder) as the predictor variables. Bold *p*-values denote statistical significance.



Appendix Figure 22: Elliptical area across fall risk. Elliptical area of the center of pressure across a clinical fall risk score by cognitive demand (a) and gender (b). The clinical fall risk was calculated from the Physiological Profile Assessment (PPA) [113]. The elliptical area is plotted for the single task (blue dots) and dual task (yellow dots) conditions and by females (light blue dots) and males (gray dots). A repeated measures linear mixed model was performed with elliptical area as the dependent variable and clincial fall risk score, cognitive demand, the interaction of fall risk score and cognitive demand, and gender (confounder) as the predictor variables. Bold *p*-values denote statistical significance.

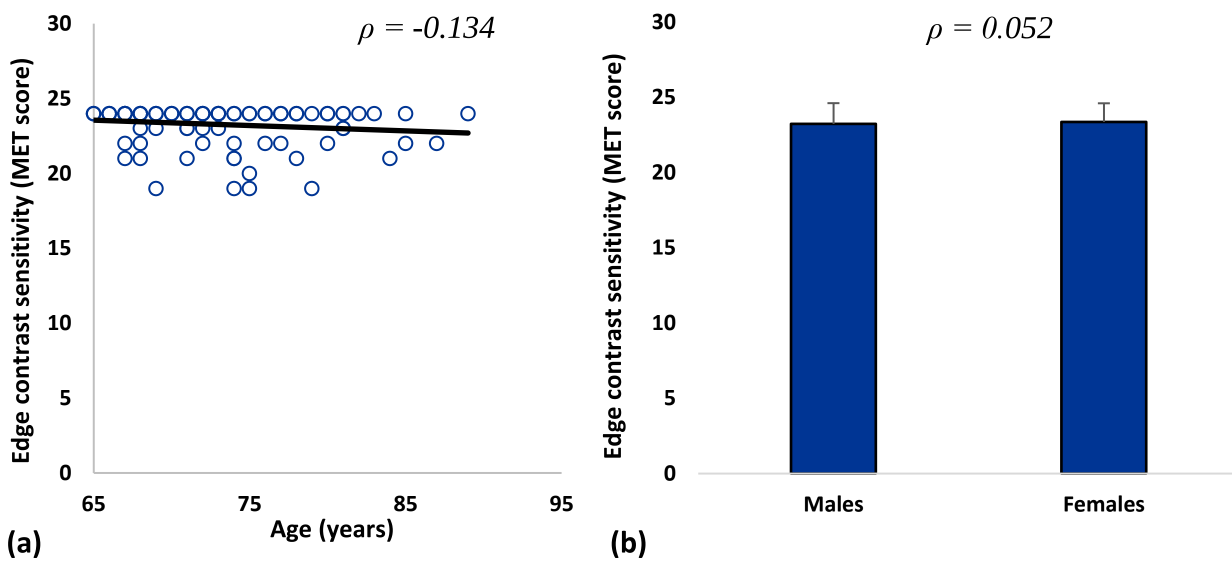
Appendix B.2.2 Correlations of task performance with age and gender

Appendix Table 2: Correlations of task peformance with age and gender. Pearson's correlations of age and gender with task performance measures for older adults. Pearson's correlations with the traditional task performance measure (z-score of elliptical area and task time) are shaded and Pearson's correlations with the ladder specific task performance measure (z-score of edge distance and task time) are non-shaded for single and dual task conditions. The mean (standard deviation) age was 72.9 (5.5) years old. Males were given a number code of 1 and females were given a number code of 0. Bold values indicate a significant correlation.

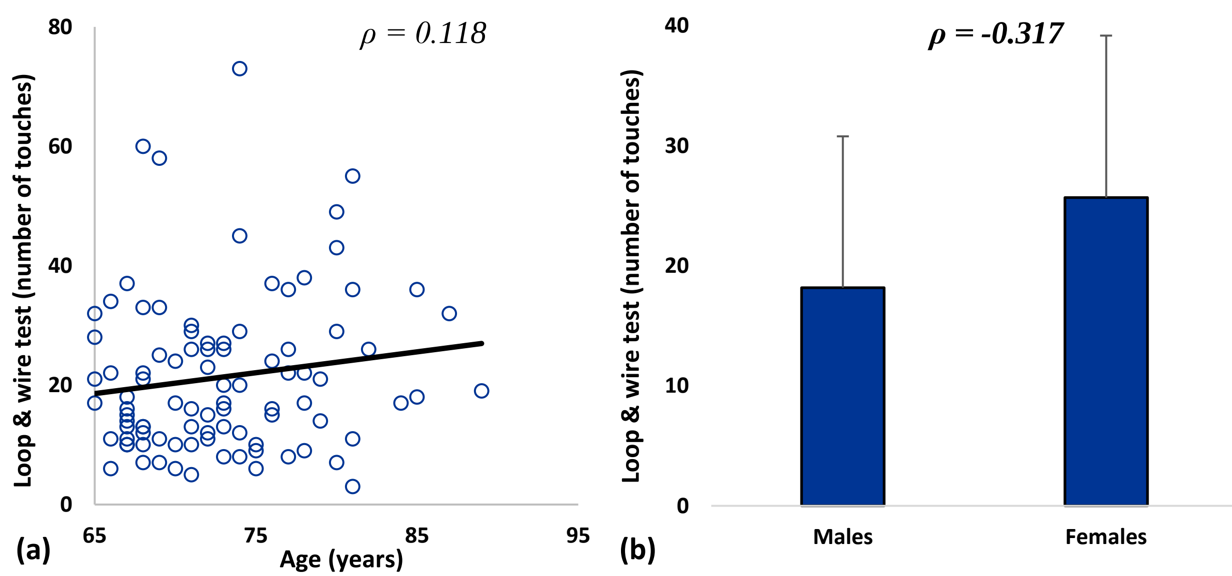
	Single task		**Dual task**	
	Traditional	Ladder specific	Traditional	Ladder specific
Age	**-0.425*** **	**-0.256***	**-0.351*** **	**-0.399*** **
Gender	-0.137	0.133	-0.148	**0.208***

$p \leq 0.05$*, $p \leq 0.01$**, $p \leq 0.001$***

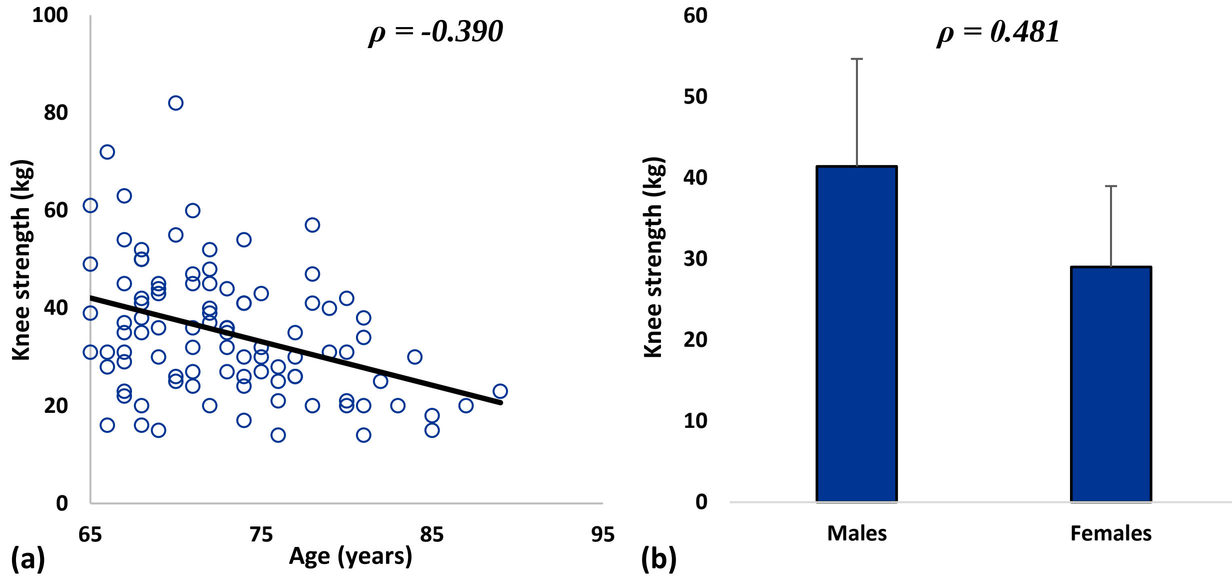
Appendix B.2.3 Correlations of individual task performance predictors with age and gender



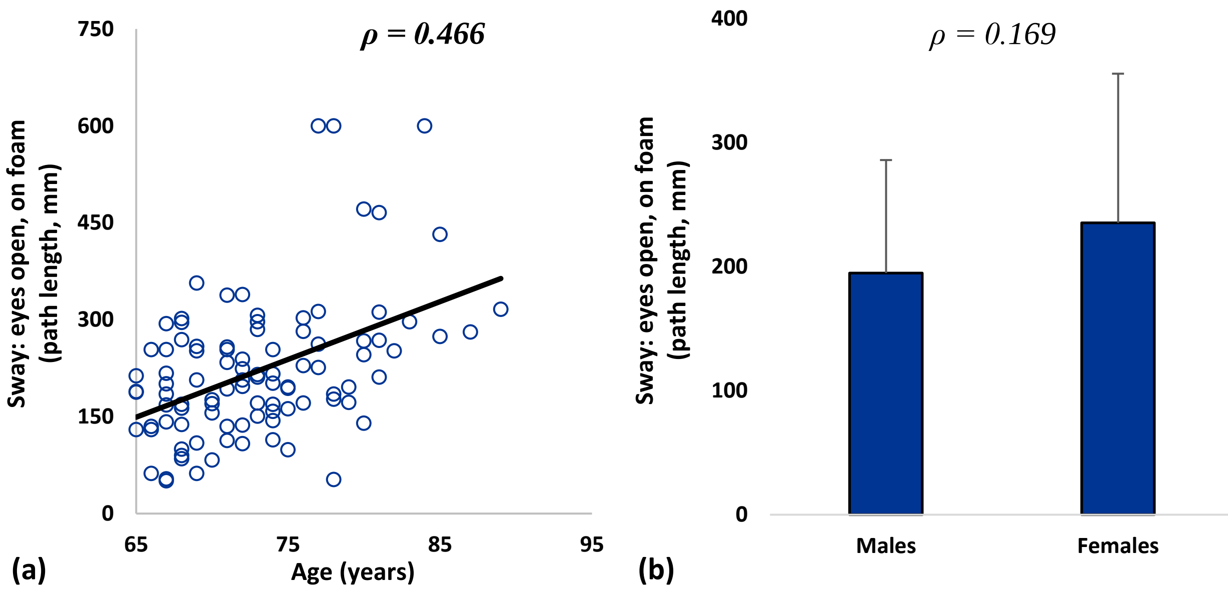
Appendix Figure 23: Edge contrast sensitivity by age and gender. Pearson's correlation with edge contrast sensitivity by age (a) and gender (b). A bold correlation denotes statistical significance.



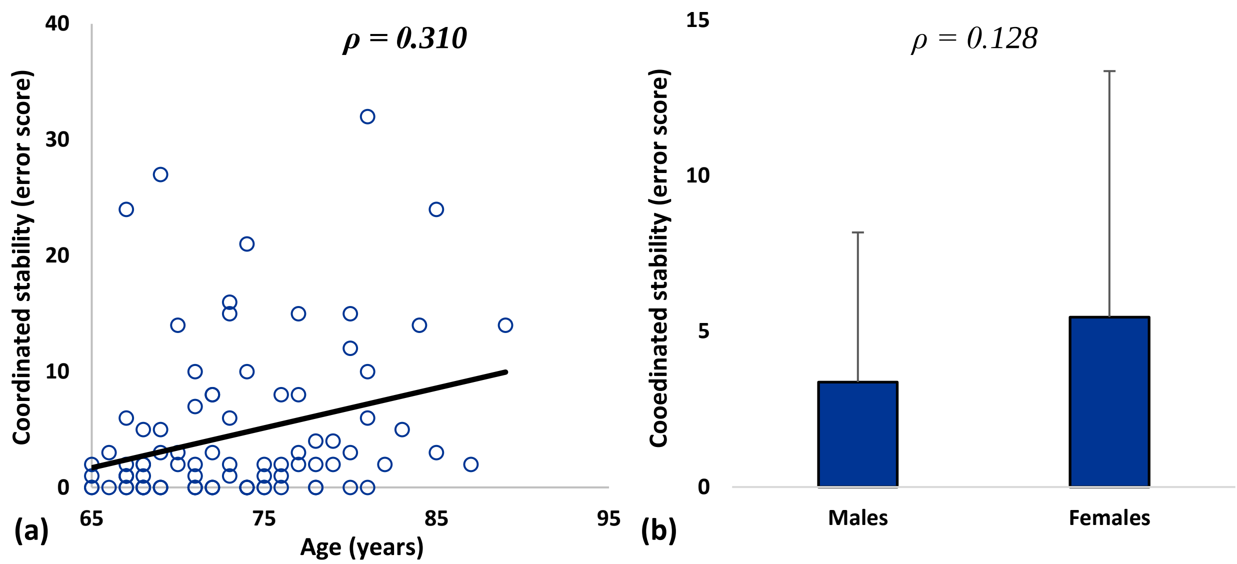
Appendix Figure 24: Loop & wire test by age and gender. Pearson's correlation with loop & wire test by age (a) and gender (b). A bold correlation denotes statistical significance.



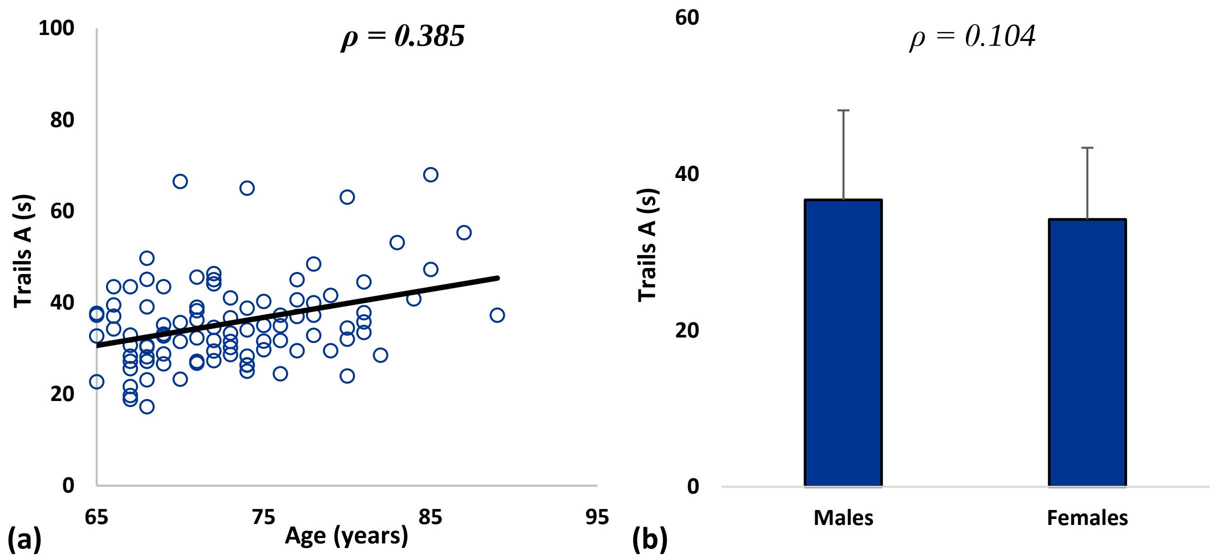
Appendix Figure 25: Knee strength by age and gender. Pearson's correlation with knee strength by age (a) and gender (b). A bold correlation denotes statistical significance.



Appendix Figure 26: Sway: eyes open, on foam by age and gender. Pearson's correlation with sway: eyes open, on foam by age (a) and gender (b). A bold correlation denotes statistical significance.

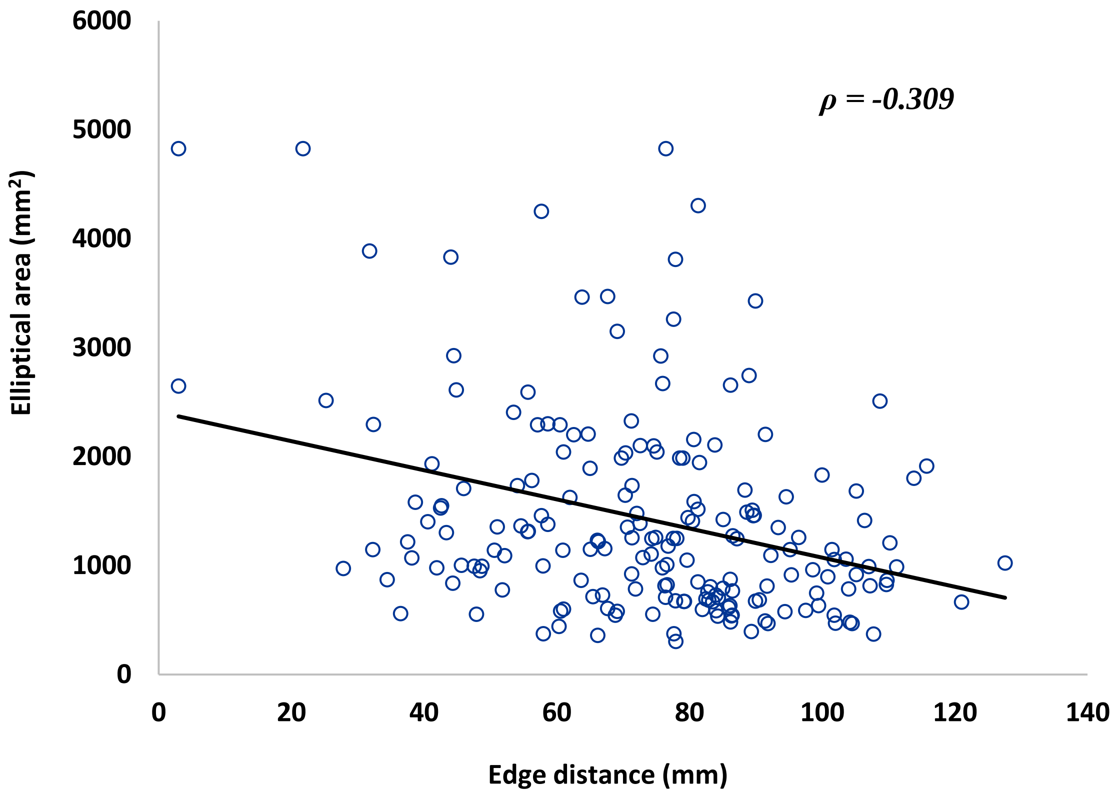


Appendix Figure 27: Coordinated stability by age and gender. Pearson's correlation with coordinated stability by age (a) and gender (b). A bold correlation denotes statistical significance.



Appendix Figure 28: Trails A by age and gender. Pearson's correlation with Trails A by age (a) and gender (b). A bold correlation denotes statistical significance.

Appendix B.2.4 Correlation of stability measures



Appendix Figure 29: Correlation of stability measures. Pearson's correlation between center of pressure elliptical area and edge distance while change a light bulb on a household stepladder. A bold correlation denotes statistical significance.

Appendix C: Individual, Environmental and Biomechanical Response Factors on Fall Recovery

Appendix C.1 Copyright Permission

Appendix C.1.1 Factors Affecting Fall Severity from a Ladder: Impact of Climbing Direction, Gloves, Gender and Adaptation

Appendix C.1.2 Effects of Upper Body Strength, Hand Placement and Foot Placement on Ladder Fall Severity

Appendix C.2 Additional Clarification

Appendix C.2.1 Releasing rung

The simulated misstep perturbation during ladder climbing released the 4th ladder rung from the bottom when the majority of the climber's weight was loaded onto this rung. This resulted in the rung falling to the floor, which is different from a real-world slip. In this experiment, participants did not have the opportunity to reestablished foot placement with the rung they experienced a slip/misstep on. Video analysis from [80] reveals participants are capable of reestablishing foot placement with the perturbation rung. The rational to release the rung was to ensure more outcomes where the participant experienced a fall. In our previous work [80], we induced climbing foot slips with a low friction rung (i.e. a rung on rotational bearings), but only 14 slips occurred from 57 potential slip trials. To better understand the recovery aspect after a climbing perturbation, we released the rung to ensure all participants would experience a ladder fall.

Appendix C.2.2 Climber experience

Participants were not asked about their ladder climbing experience and participants did not need ladder climbing experience to be eligible for this study.

Appendix C.3 Methodology

Appendix C.3.1 Lost data

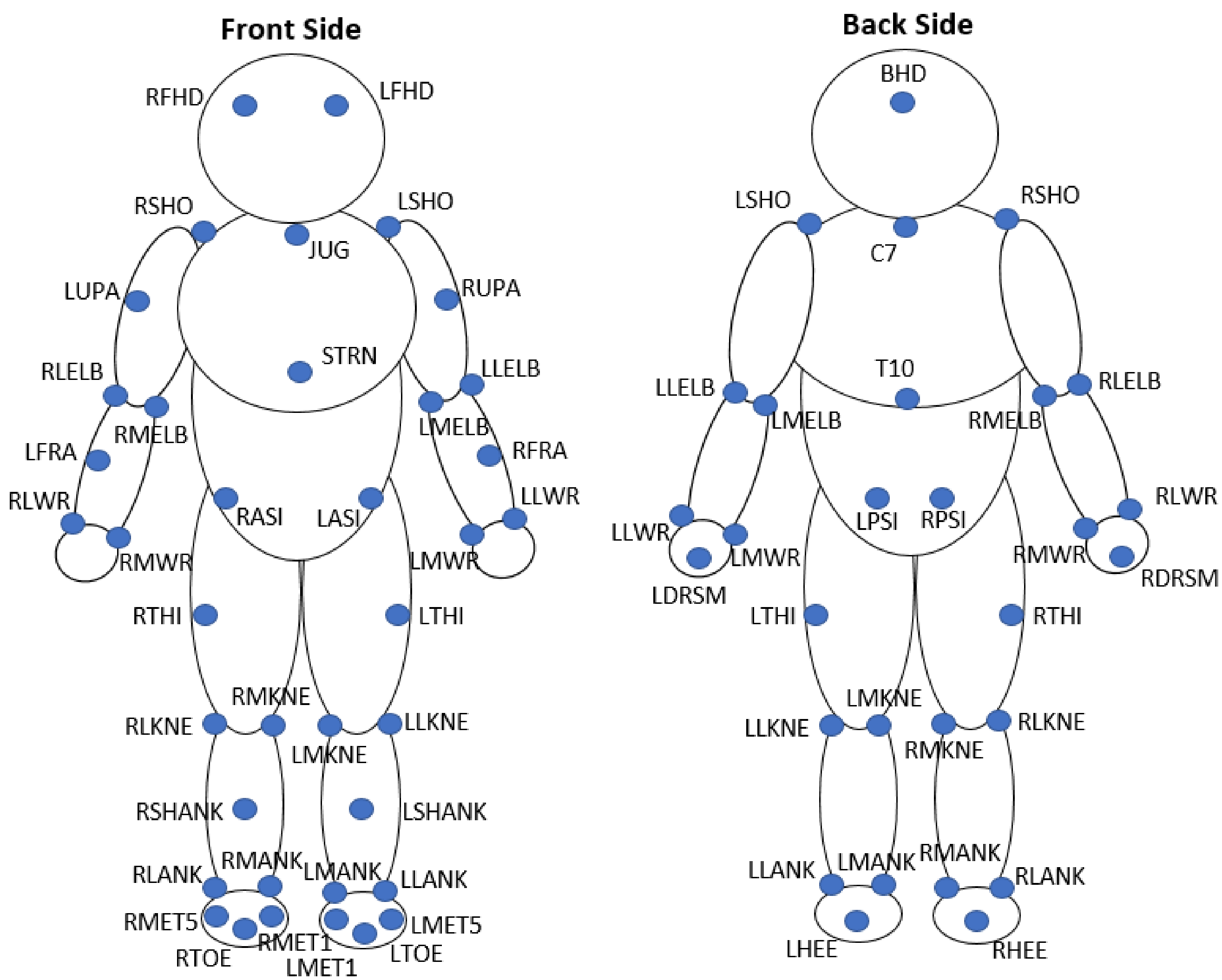
Appendix Table 3: Participant data by completeness and study. Participants with complete data, partial data (due to equipment error or withdrawal) and no data (due to equipment error). Lost data due to incongruence between an algorithm and visual inspection for peak harness force is not considered partial data because this data was processed for analysis. Total number of participants recruited and analyzed by study is listed.

	Complete data	Partial data	No data	Total
Participants	28	3	4	35
4.1	28	3	0	31
4.2	28	0	0	28
4.3	28	3	0	31

Appendix Table 4: Lost trials. The number of participants and the trials lost per participant due to equipment error, participant withdrawal, or incongruence between an algorithm and visual insepection for peak harness force. The total number of trials lost per cause is listed.

	Participants	Trials	Total
Equipment error	4	6	26
	1	2	
Withdrawal	2	4	8
Incongruence between algorithm and visual inspection	4	1	9
	1	2	
	1	3	

Appendix C.3.2 Climber marker template

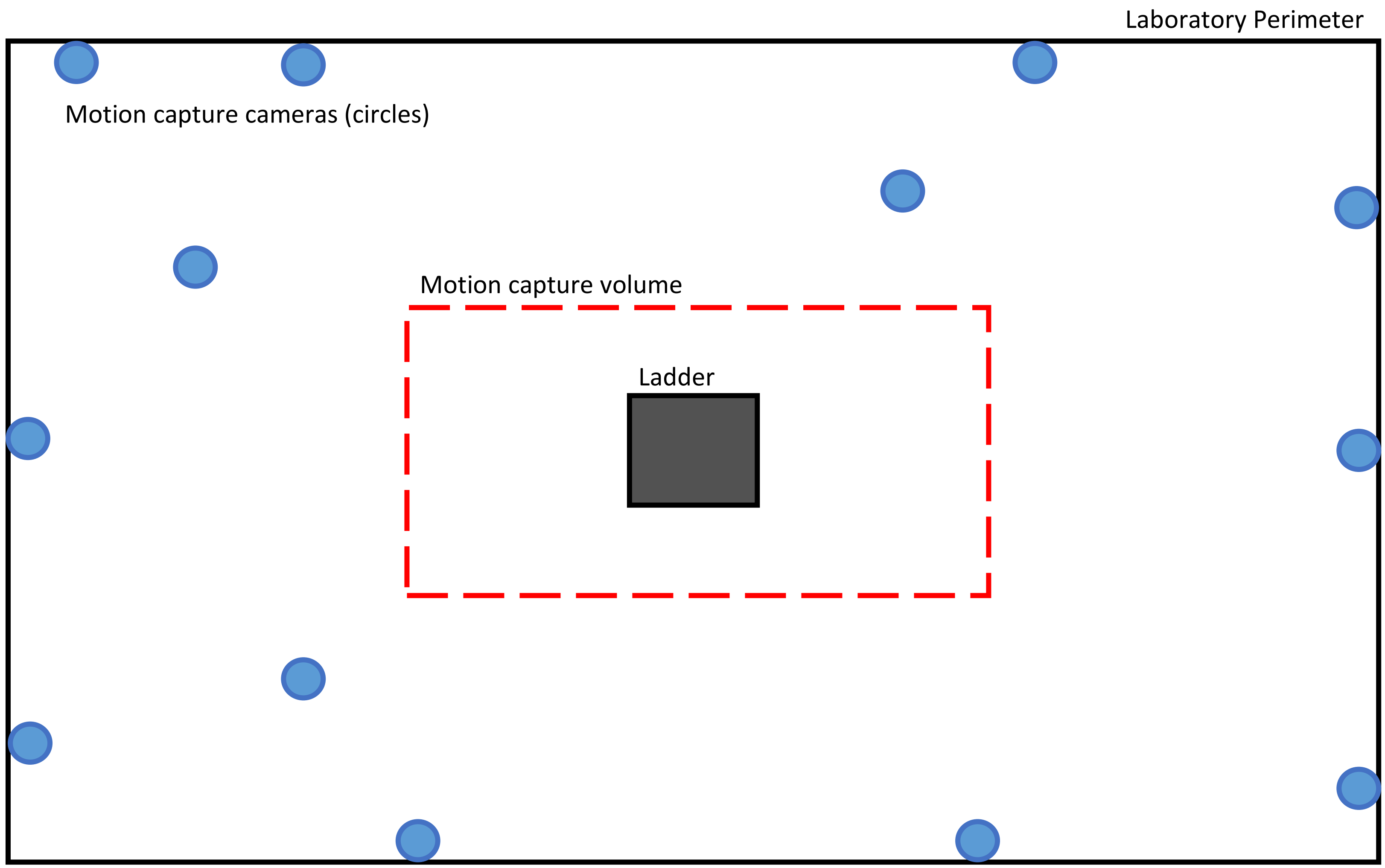


Appendix C.3.3 Abbreviations of climber markers

LFHD	Left front head
RFHD	Right font head
BHD	Back head
C7	7^{th} cervical vertebrae
T10	10^{th} thoracic vertebrae
JUG	Jugular notch
STRN	Sternum
LSHO	Left shoulder
LUPA	Left upper arm
LLELB	Left lateral elbow
LMELB	Left medial elbow
LFRA	Left forearm
LLWR	Left lateral wrist
LMWR	Left medial wrist
LFIN	Left finger
RSHO	Right shoulder
RUPA	Right upper arm
RLELB	Right lateral elbow
RMELB	Right medial elbow
RFRA	Right forearm
RLWR	Right lateral wrist
RMWR	Right medial wrist
RFIN	Right finger
LASI	Left ASIS
RASI	Right ASIS

LPSI	Left PSIS
RPSI	Right PSIS
LTHI	Left thigh
LLKNE	Left lateral knee
LMKNE	Left medial knee
LSHANK	Left shank
LLANK	Left lateral ankle
LMANK	Left medial ankle
LHEE	Left heel
LMET1	Left metatarsal 1
LMET5	Left metatarsal 5
LTOE	Left toe
RTHI	Right thigh
RLKNE	Right lateral knee
RMKNE	Right medial knee
RSHANK	Right shank
RLANK	Right lateral ankle
RMANK	Right medial ankle
RHEE	Right heel
RMET1	Right metatarsal 1
RMET5	Right metatarsal 5
RTOE	Right toe

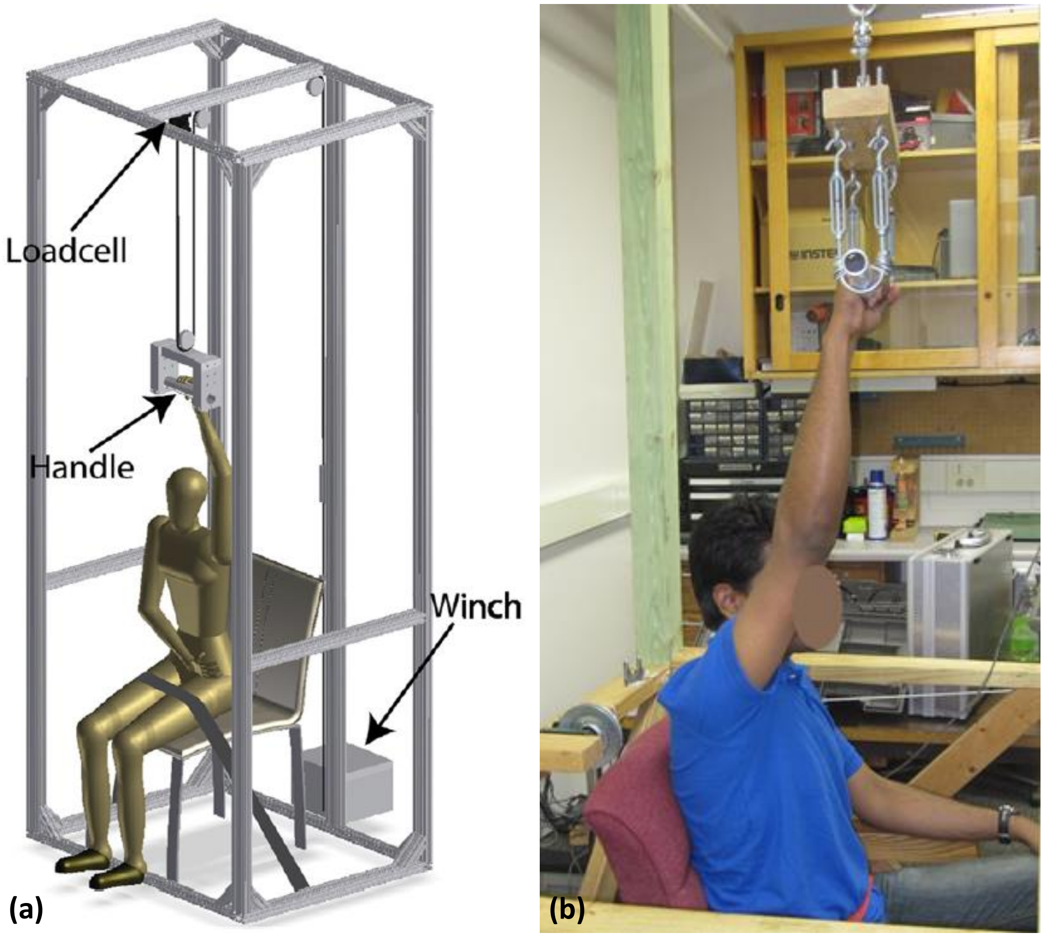
Appendix C.3.4 Motion capture volume with ladder and setup



Appendix C.3.5 High friction and low friction gloves

Appendix Figure 30: High friction and low friction glove condition. The high friction glove (left) is made of knitted fabric with a latex palm and the low friction glove (right) is made of 100% cotton.

Appendix C.3.6 Breakaway strength testing apparatus



Appendix Figure 31: Schematic of the breakaway strength test. Computer designed apparatus of the breakaway strength test (a) and an image of a breakaway strength testing session (b). A handhold is raised through a pulley system connected to a winch. A load cell inline with the pulley system records the force generated onto the handhold prior to hand decoupling. The participant is secured in a seated position throughout the testing session.

Appendix Figure 31.a reprinted from Journal of Biomechanics, 45 (6), Hur, P., B. Motawar, N.J. Seo, *Hand breakaway strength model – Effects of glove use and handle shapes on a person's hand strength to hold onto handles to prevent fall from elevation*, 958-964. Copyright © 2012, with permission from Elsevier. https://doi.org/10.1016/j.jbiomech.2012.01.013

Appendix Figure 31.b reprinted from Human Factors, 60 (2), Beschorner, K.E., G.P, Slota, E.M. Pliner, E. Spaho, N.J. Seo, *Effects of Gloves and Pulling Task on Achievable Downward Pull Forces on a Rung*, 191-200. Copyright © 2018, © SAGE Publications. https://doi.org/10.1177/0018720817742515

Appendix C.3.7 Mid-hip joint center calculation

Pelvic Width (PW) is the distance between the ASIS markers.

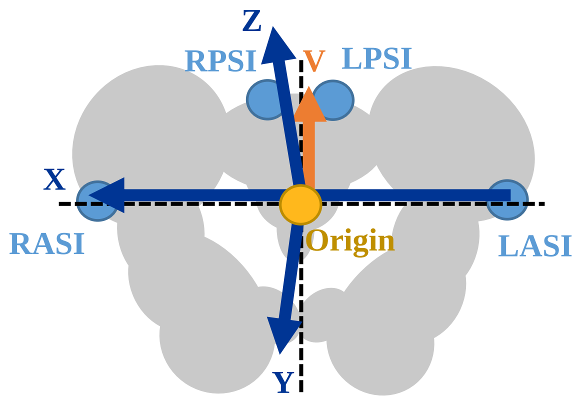
$$PW = |Right\ ASIS - Left\ ASIS|$$

Bell's Method used to calculate the coordinate location (X, Y, Z) of the Right Hip Joint Center of the Pelvis ($RHJC_{Pelvis}$) and Left Hip Joint Center of the Pelvis ($LHJC_{Pelvis}$) within the pelvic coordinate system.

$$RHJC_{Pelvis} = [-0.19 * PW;\ -0.30 * PW; 0.36 * PW]$$

$$LHJC_{Pelvis} = [-0.19 * PW;\ -0.30 * PW; -0.36 * PW]$$

The RHJC and LHJC are calculated in the pelvic coordinate system and were transformed into the global coordinate system. To create this transform, the global to pelvic coordinate system was created from the right ASIS (RASI), left ASIS (LASI), right PSIS (RPSI) and left PSIS (LPSI) markers.



Appendix Figure 32: Pelvic coordinate system. The coordinate system (dark blue arrows) of the pelvis (gray) was created from the ASIS and PSIS markers (light blue circles). The origin (yellow circle) of the pelvic coordinate system was the center of the right and left ASIS markers.

The following equations were used to calculate the global to pelvic coordinate system.

$$Origin_{pelvis} = \frac{RASI + LASI}{2}$$

$$X_{pelvis} = RASI - LASI$$

$$Mid\ PSIS = \frac{RPSI + LPSI}{2}$$

$$V_{pelvis} = Mid\ PSIS - Origin_{pelvis}$$

$$Z_{pelvis} = V_{pelvis} \times X_{pelvis}$$

$$Y_{pelvis} = Z_{pelvis} \times X_{pelvis}$$

The X, Y and Z vectors of the pelvis were normalized by the corresponding vector magnitude. The origin (O) and vectors of the pelvis were entered into a matrix to form the transformation matrix from the global to pelvic coordinate system (T_{G_Pelvis}).

$$T_{G\_Pelvis} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ \{\vec{O}\} & \{\vec{X}\} & \{\vec{Y}\} & \{\vec{Z}\} \end{bmatrix}$$

$$T_{G\_Pelvis} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ O_x & X_x & Y_x & Z_x \\ O_y & X_y & Y_y & Z_y \\ O_z & X_z & Y_z & Z_z \end{bmatrix}$$

The global RHJC ($RHJC_G$) and LHJC ($LHJC_G$) were created by multiplying the global to pelvic transformation matrix by the RHJC and LHJC in the pelvic coordinate system.

$$RHJC_G = T_{G\_Pelvis} * RHJC_{Pelvis}$$

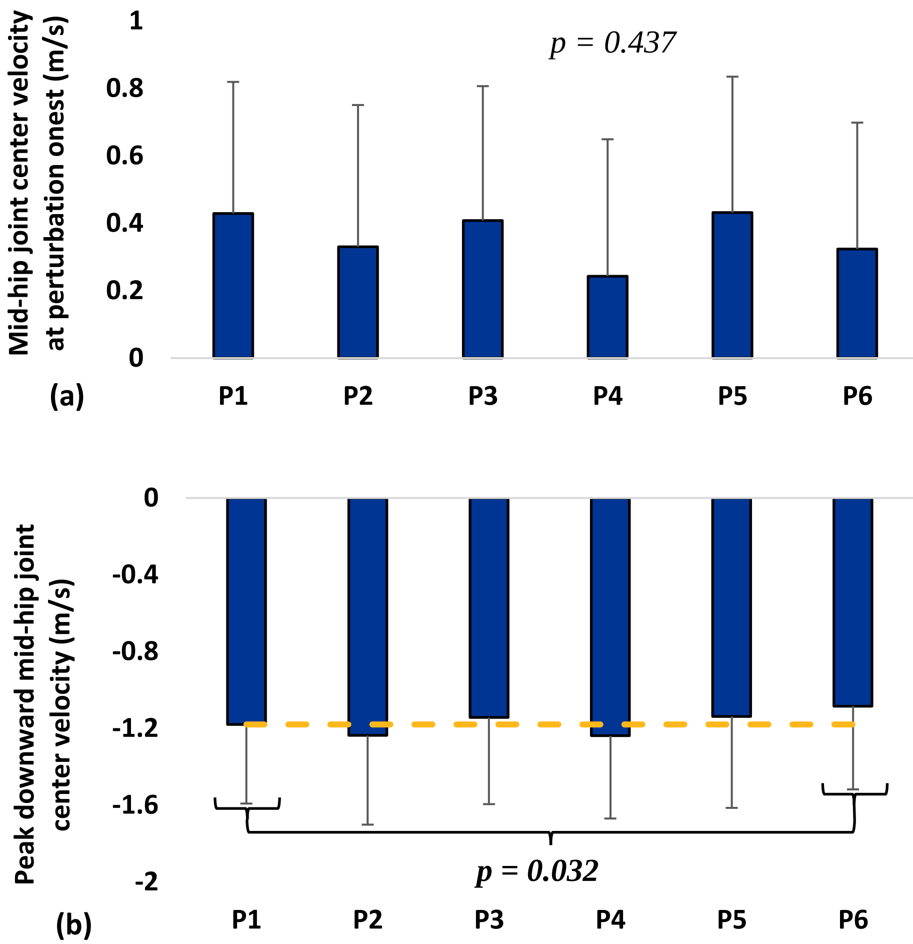
$$LHJC_G = T_{G\_Pelvis} * LHJC_{Pelvis}$$

The Mid-Hip Joint Center (MHJC) was calculated from the midpoint of the global RHJC and LHJC locations.

$$MHJC = \frac{RHJC + LHJC}{2}$$

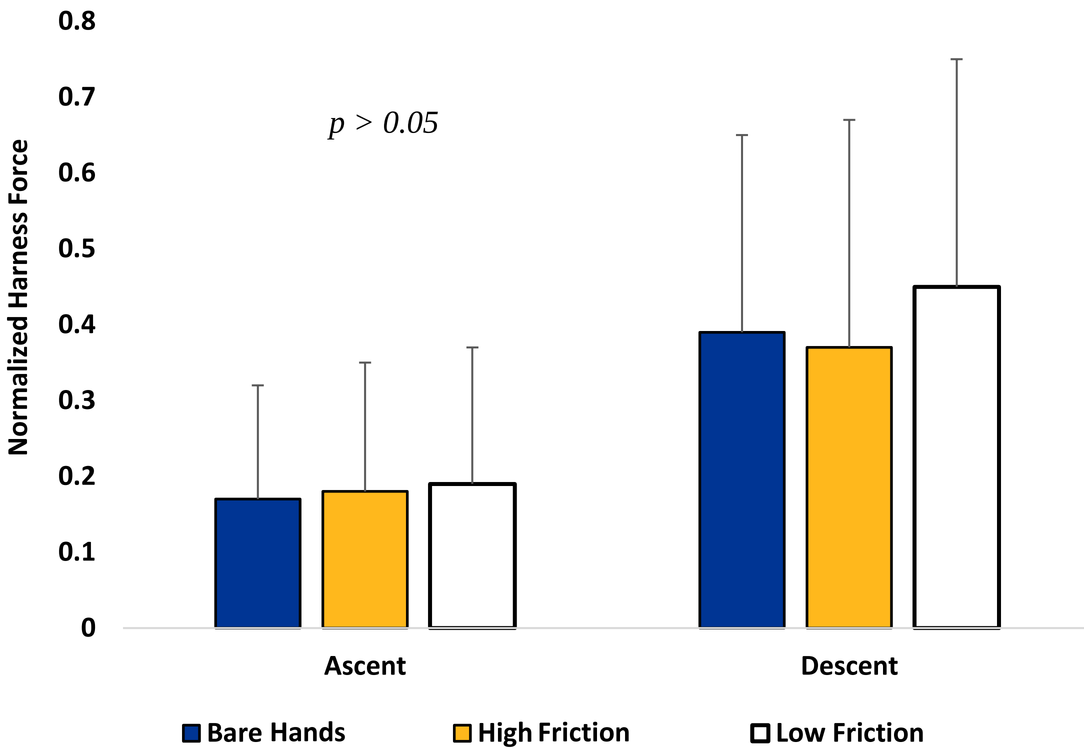
Appendix C.4 Supplementary Analyses

Appendix C.4.1 Mid-hip joint center velocity by perturbation number



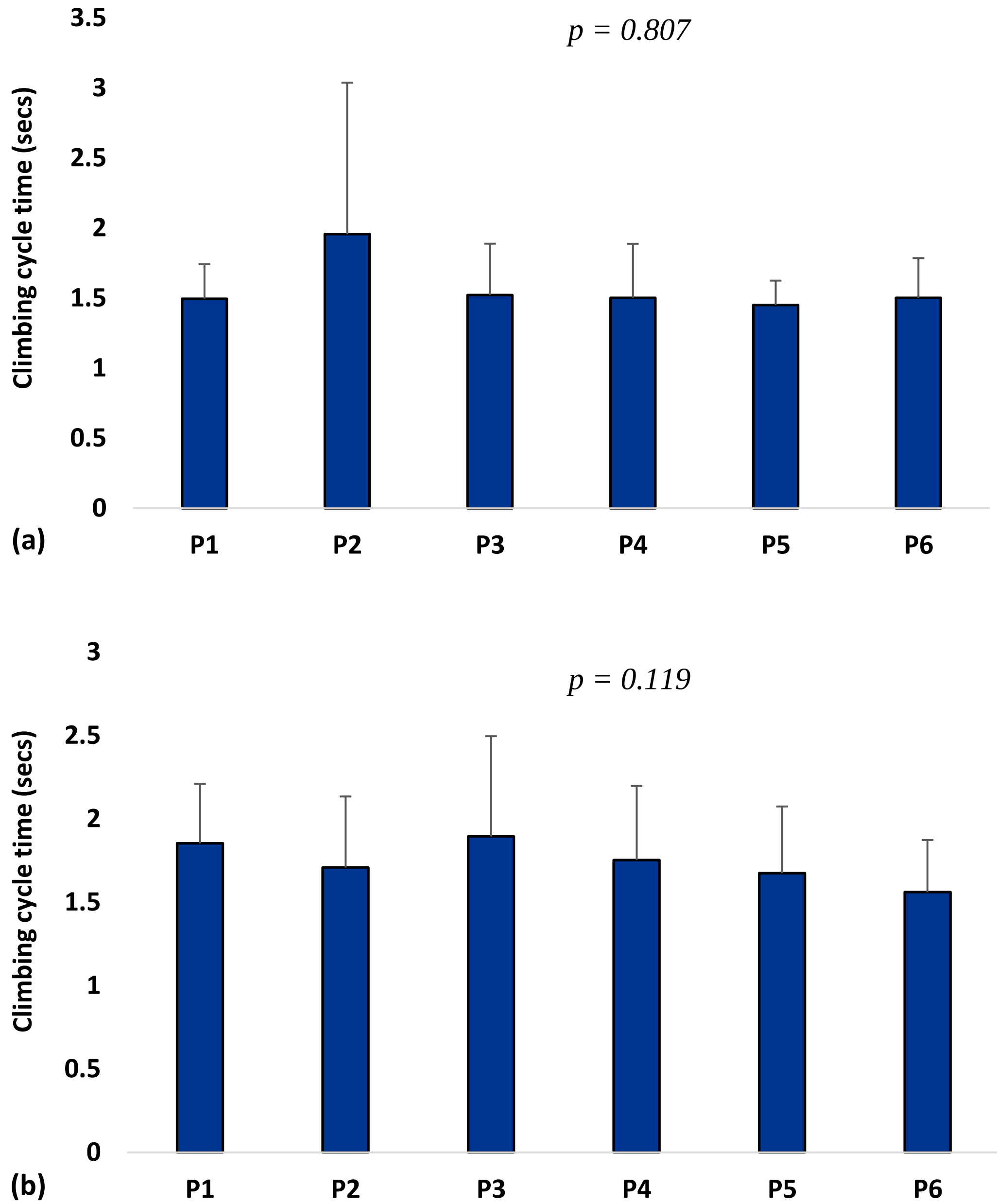
Appendix Figure 33: Mid-hip joint center velocity by perturbation number. Mean mid-hip joint center velocity at perturbation onset (a) and mean peak downward velocity of the mid-hip joint center (b) by perturbation. Error bars denote standard deviations. The yellow dashed line indicates the mean peak downward velocity of the mid-hip joint center for the first perturbation. Error bars denote standard deviations. Bold *p*-values denote statistical significance.

Appendix C.4.2 Harness force by glove condition



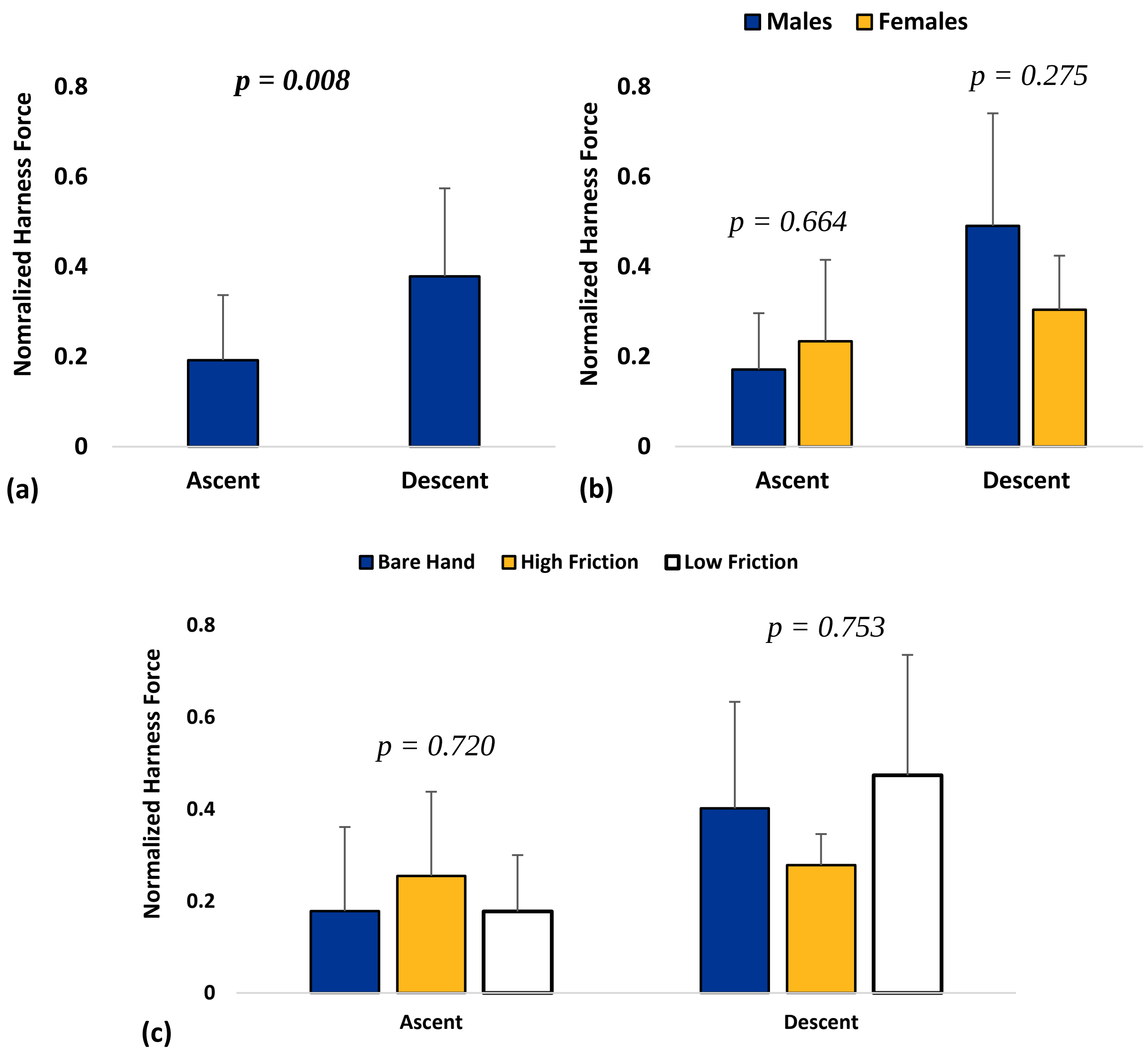
Appendix Figure 34: Harness force by glove condition. Mean normalized harness force for bare hands (blue), high friction (yellow) and low friction (white) glove condition after an ascending and descending perturbation. Error bars denote standard deviations. A bold *p*-value denotes statistical significance.

Appendix C.4.3 Climbing cycle time by perturbation number



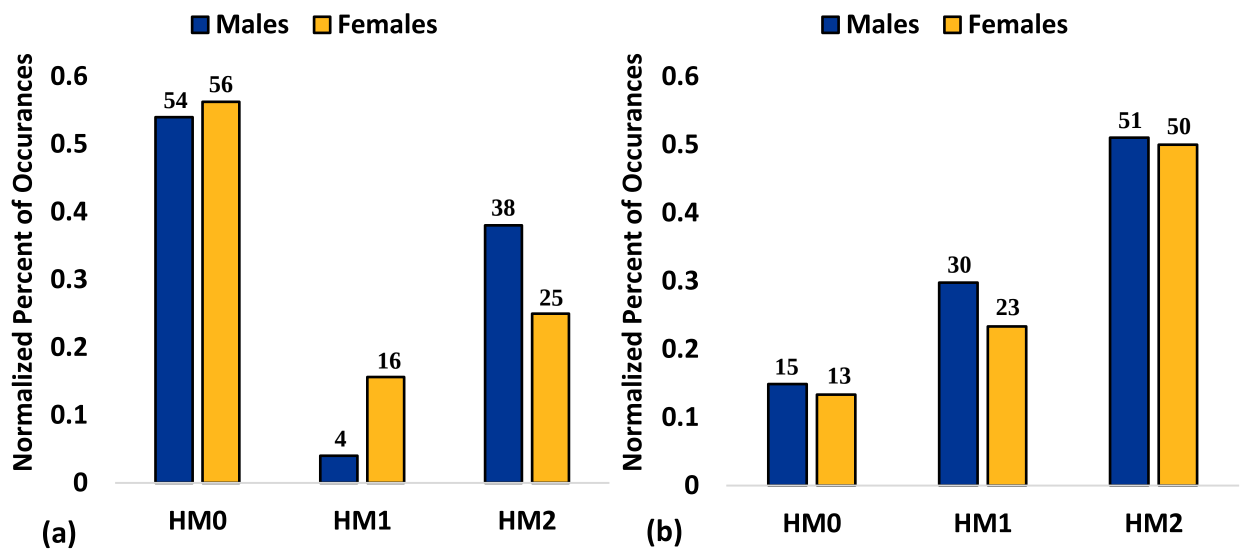
Appendix Figure 35: Climbing cycle time by perturbation number. The mean climbing cycle time by perturbation for ascent (a) and descent (b). Error bars denote standard deviations.

Appendix C.4.4 Harness force for first perturbations by climbing direction, gender and glove condition

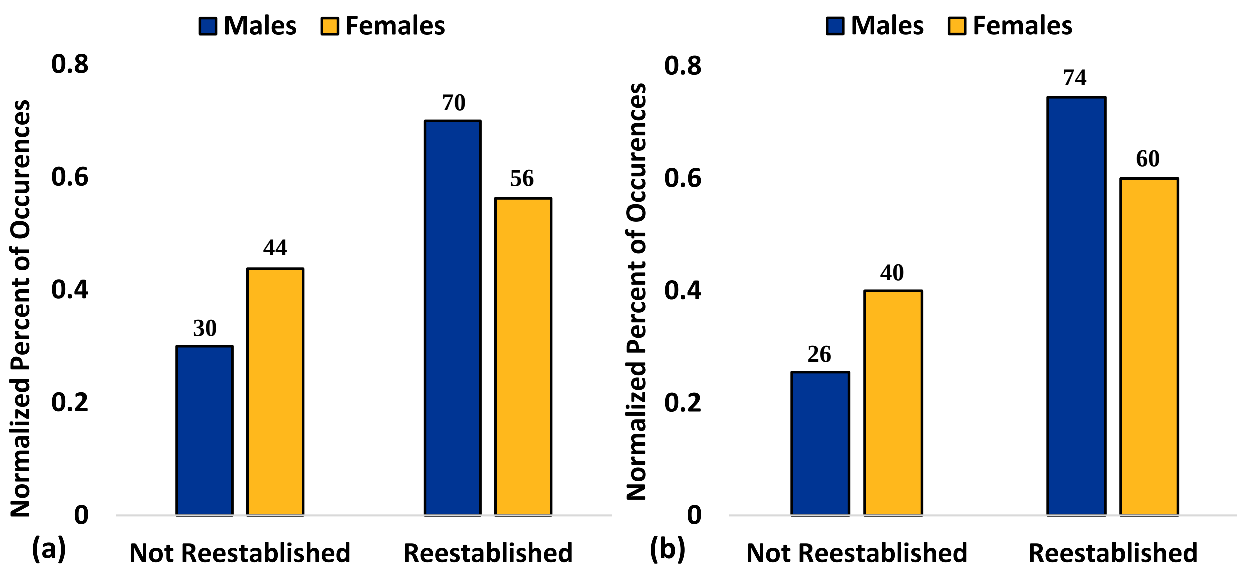


Appendix Figure 36: Harness force for first perturbations by climbing direction, gender and glove condition. Statistical analyses were consistent with those in 4.1, but pertubration number and interactions were removed from the models. First perturbation results were similar to the results reported in 4.1. Descending perturbation resulted in higher normalized harness forces (a); normalized harness force values were similar between males and females for the first pertubation (b); and glove condition did not affect normalized harness force (c). Error bars denote standard deviations. Bold *p*-values denote statistical significance.

Appendix C.4.5 Hand and foot placement response by gender

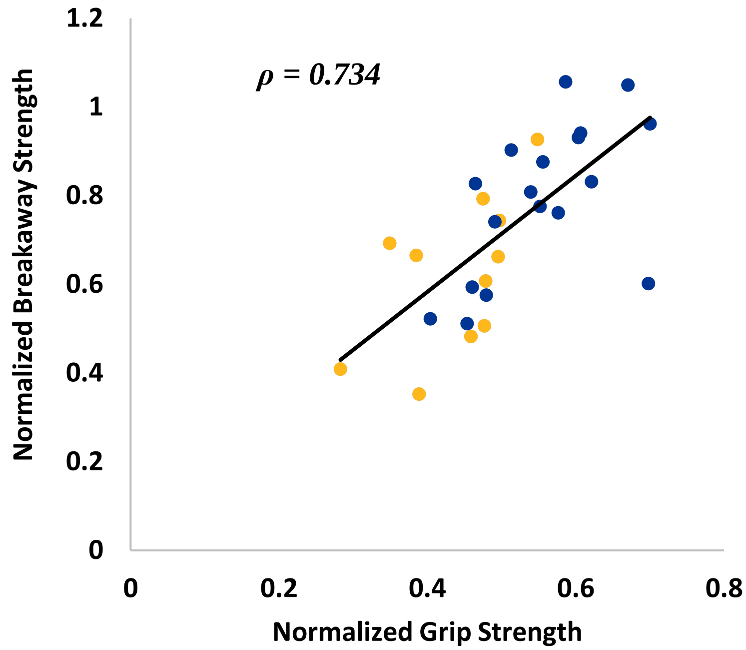


Appendix Figure 37: Occurrence of hand placement response by gender. Percent of hand placement occurrence (normalized by total hand placement response by gender) for males and females after an ascending (a) and descending (b) perturbation. The percentage of occurrence is displayed above each hand placement response. Three common hand placements were observed from the hand that moved or the hand that was about to move after the climbing perturbation: HM2 – hand moved two rungs from initial position; HM1 – hand moved one rung from initial position; HM0 – hand may have elevated, but did not leave the initial position (see 4.2.3.3 and Figure 4.2.1 for more details). The movement direction was consistent with the climbing direction (i.e. HM2 would signify the hand moved two rungs up for ascent or two rungs down for descent). After an ascending perturbation, males were more likely to reach up two rungs compared to females and females were more likely to only reach up one rung compared to males. Similar responses between males and females were observed after a descending perturbation where the hand is reaching down. Females may have a harder time reaching to higher rungs.



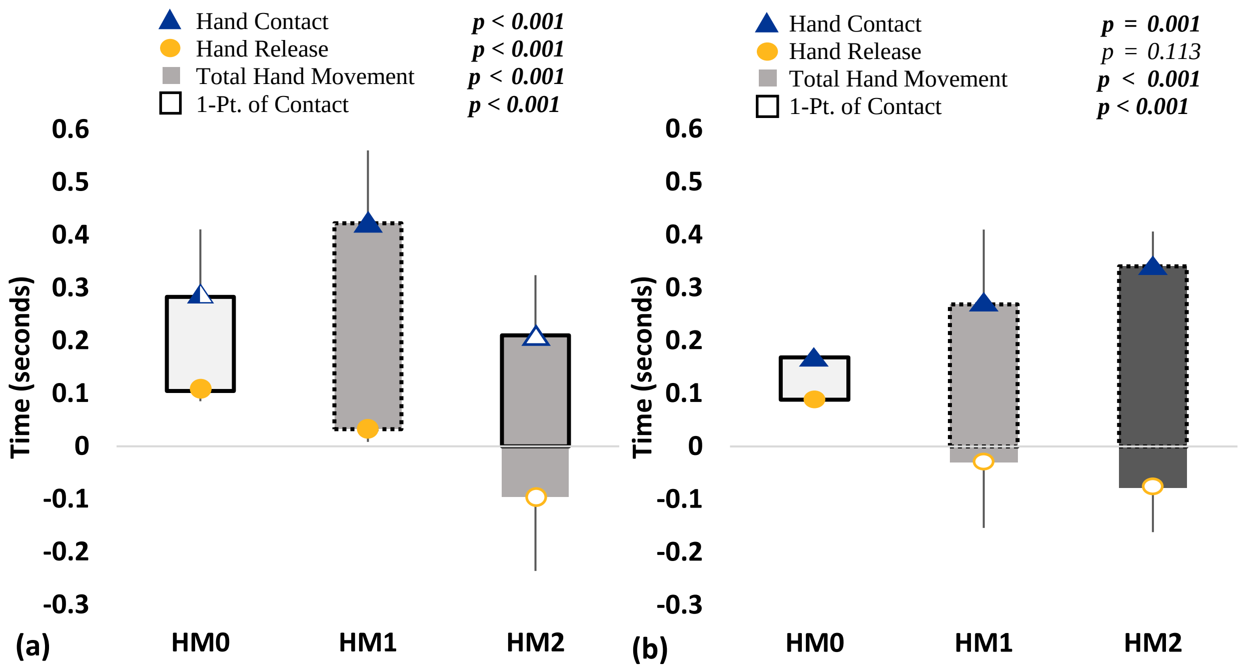
Appendix Figure 38: Occurrence of foot placement response by gender. Percent of foot placement occurrence (normalized by total foot placement response by gender) for males and females after an ascending (a) and descending (b) perturbation. The percentage of occurrence is displayed above each foot placement response. Two foot placement resopnses were observed: Reestablished – at least one foot reestablished and maintained contact with the ladder rung after the climbing perturbation; Not Reestablished – neither foot reestablished and maintained contact with the ladder rung(s) after the climbing pertubation (see 4.2.3.3 and Figure 4.2.1 for more details). After ascending and descending perturbations, males were more likely to reestablish foot placement than females. Females may have a harder time extending their legs to reestablish foot placement.

Appendix C.4.6 Correlation between breakaway and grip strength



Appendix Figure 39: Relationship between breakaway and grip strength. Normalized breakaway strength with normalized breakaway strength. Male participants are represented by the blue dots and female participants are represented by the yellow dots. The solid line represents the best linear fit. Spearman's correlation (ρ) is displayed on the graph. A bold correlation denotes statistical significance.

Appendix C.4.7 Temporal differences in hand placement response

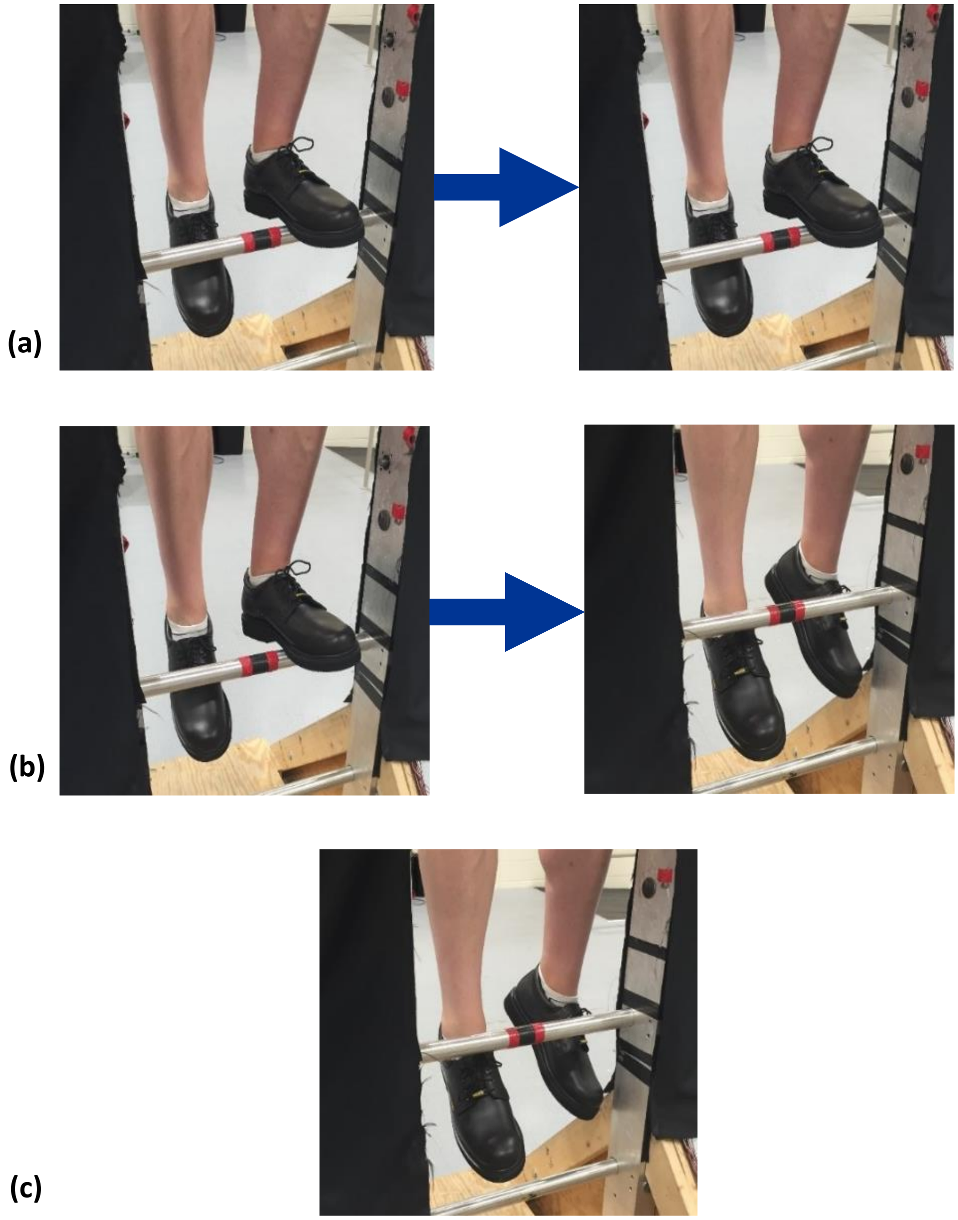


Appendix Figure 40: Temporal parameters by hand placement. Mean hand release (yellow circle), hand contact (blue triangle), total hand movement (length of gray square) and 1-pt. of contact (length of outlined square) times for hand placement (HM) response after ascending (a) and descending (b) climbing perturbations. Time zero represents perturbation onset. An ANOVA was performed for each temporal measure with hand placement response as the predictor variable. Tukey HSD post-hoc analyses were performed when temporal measures differed by hand placement response. HM2 – hand moved two rungs from initial position; HM1 – hand moved one rung from initial position; HM0 – hand elevated and returned to initial position. Negative values for the hand release time indicate the hand left the rung prior to perturbation onset. Error bars represent standard deviations for hand release (negative bars) and hand contact (positive bars) times. Significantly different times between hand placement response are indicated by bold *p*-values, unmatched shaded shapes and unmatched outlined patterns.

Appendix C.4.8 Foot-rung contact of the perturbed foot

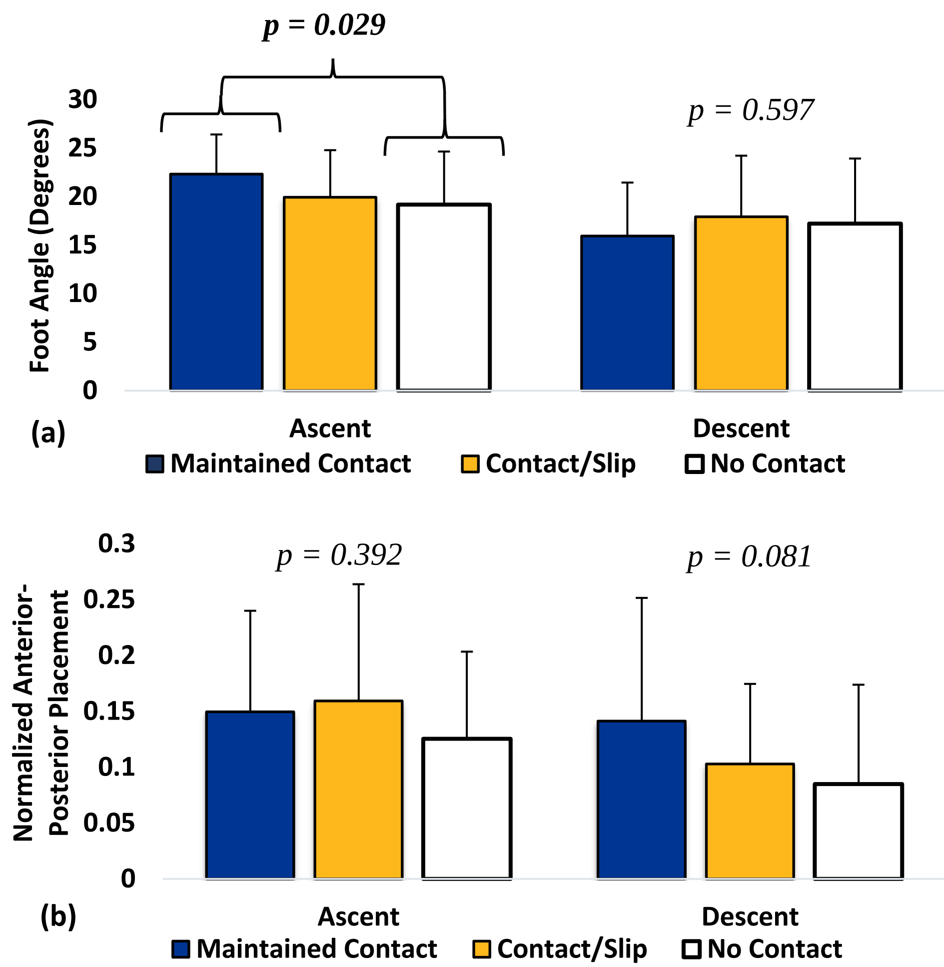
Appendix Table 5: Foot-rung contact of the perturbed foot. Number (percent) of foot-rung contact of the perturbed foot after a climbing perturbation. Foot-rung contact was classified as maintained contact – the foot contacted a ladder rung aftar the climbing perturbation and maintained contact with the rung; contact/slip – the foot contacted the ladder rung and slipped off; or no contact – the foot did not contact a ladder rung after the climbing perturbation. Maintained contact of the perturbed foot would lead to a reestablished foot placement (shaded). Contact/slip and no contact outcomes may have resulted in not reestablished foot placement if the unperturbed foot did not maintain contact.

	Maintained contact	**Contact/slip**	**No contact**
Ascent	35 (40%)	20 (23%)	32 (37%)
Descent	21 (26%)	19 (24%)	40 (50%)



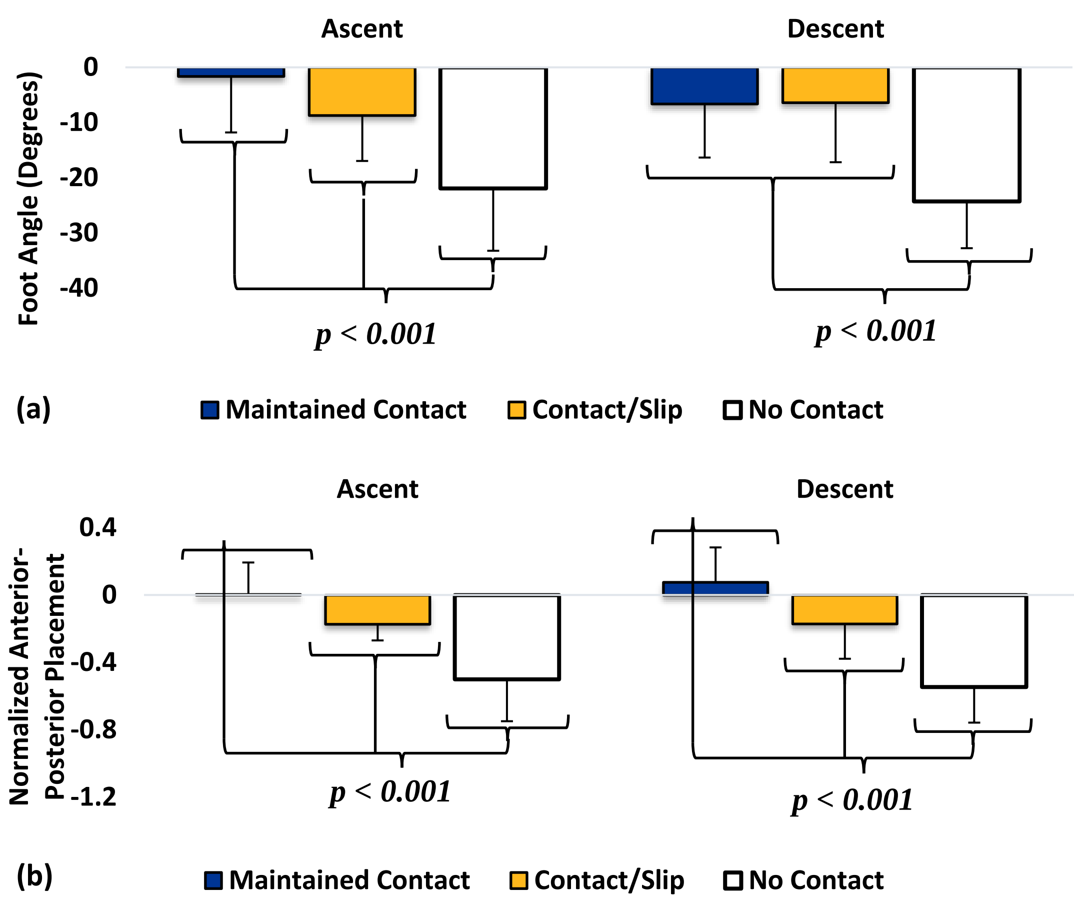
Appendix Figure 41: Foot-rung contact outcomes. Schematic of the perturbed foot maintaining foot-rung contact (a), contacting the rung than slipping (b) and not contacting the rung (c) after a ladder climbing perturbation.

Appendix C.4.9 Foot position at perturbation onset



Appendix Figure 42: Foot angle and anterior-posterior foot position at perturbation onset. Foot angle from the horiztonal (positive angle indicates the toe marker is superior to the heel marker) (a) and the anterior-posterior placement of the toe marker anterior (positive value) to the ladder rung midpoint (normalized by participant foot length) (b) of the perturbed foot at perturbation onset for maintained contact (blue), contact/slip (yellow), and no contact (white) foot-rung contact outcomes. An ANOVA was performed for foot angle and anterior-posterior foot placement at perturbation onset with foot-rung contact outcome as the predictor variable by climbing direction. Tukey HSD post-hoc analyses were performed when foot position measures differed by foot-rung contact outcome. Methods for foot angle and anterior-posterior foot position calculation are similar to our previous work [80]. Error bars denote standard deviations. Bold *p*-values denote statistical significance

Appendix C.4.10 Foot position at foot-rung contact or pass



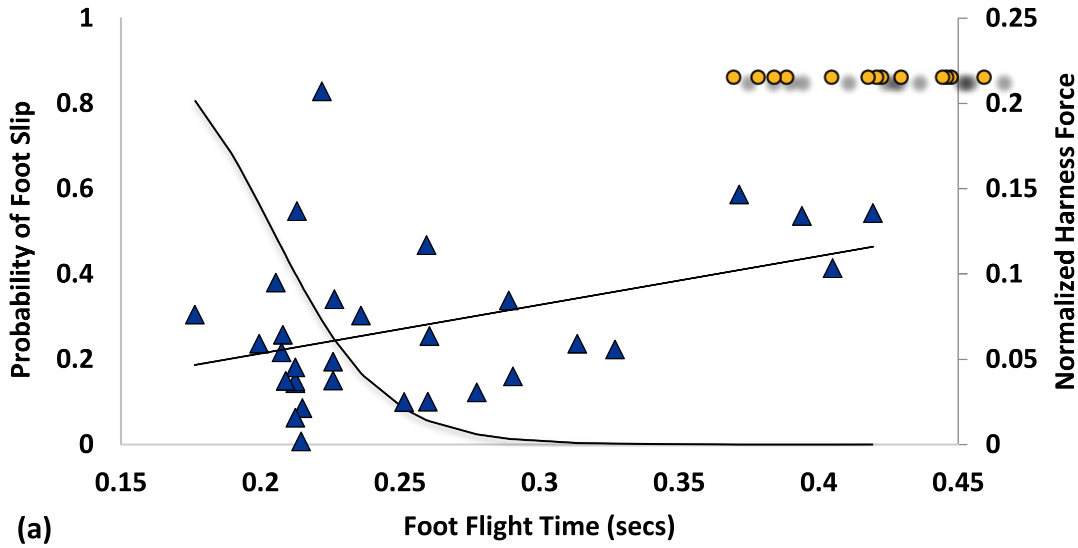
Appendix Figure 43: Foot angle and anterior-posterior foot position at foot-rung contact or pass. Foot angle from the horiztonal (positive angle indicates the toe marker is superior to the heel marker) (a) and the anterior-posterior placement of the toe marker anterior (positive value) to the ladder rung midpoint (normalized by participant foot length) (b) of the perturbed foot at foot-rung contact or pass for maintained contact (blue), contact/slip (yellow), and no contact (white) foot-rung contact outcomes. Cases where the foot did not contact the rung, the position of the foot is found when the toe marker passes the vertical ladder rung midpoint. An ANOVA was performed for foot angle and anterior-posterior foot placement at foot-rung contact or pass with foot-rung contact outcome as the predictor variable by climbing direction. Tukey HSD post-hoc analyses were performed when foot position measures differed by foot-rung contact outcome. Methods for foot angle and anterior-posterior foot position calculation are similar to our previous work [80]. Error bars denote standard deviations. Bold *p*-values denote statistical significance.

Appendix C.4.11 Probability of a foot slip after foot-rung contact

$$Slip\ Risk = \frac{1}{(1+e^{\wedge}(-10.44+51.01(Foot\ Flight\ Time))}$$

$p_{footSlip} < 0.001$

$p_{harnessForce} = 0.022$

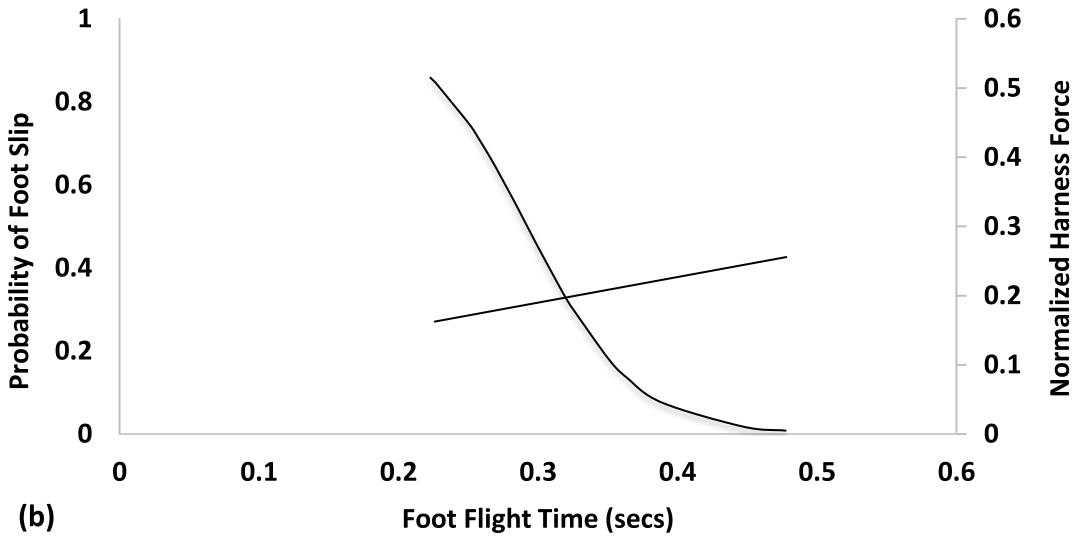


(a)

$$Slip\ Risk = \frac{1}{(1+e^{\wedge}(-7.58+25.94(Foot\ Flight\ Time))}$$

$p_{footSlip} = 0.007$

$p_{harnessForce} = 0.601$

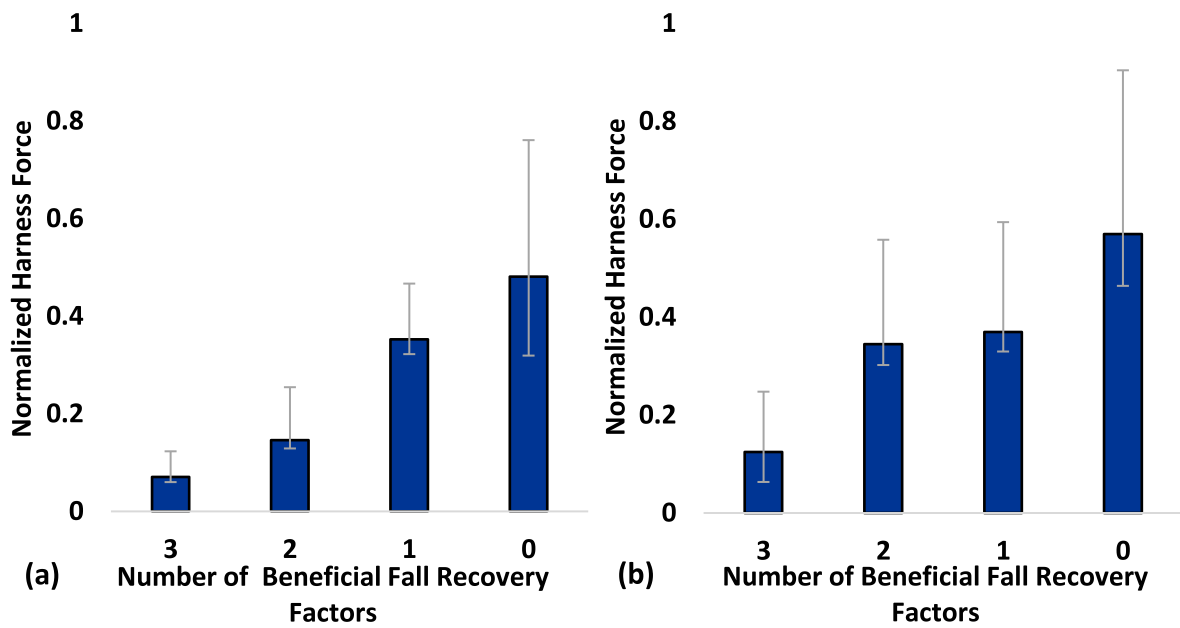


(b)

Appendix Figure 44: Foot slip and harness force by foot flight time. Probability of a foot slip (left vertical axis) after foot-rung contact of the perturbed foot by foot flight time for contact/slip (yellow dots = 1) and

maintained contact (yellow dots = 0) outcomes after an ascending (a) and descending (b) perturbation. Foot flight time is the time from perturbation onest to foot-rung contact. Logistical regressions were performed by climbing direction with slip outcome (maintained contact = 0; contact/slip = 1) as the dependent variable and foot flight time as the predictor variable. Logistical regressions and equations of foot slip probability are plotted on the graphs. Normalized harness force (right vertical axis) for only maintained contact outcomes (blue triangles) is plotted by foot flight time. Linear regressions were performed by climbing direction for the maintained contact outcomes with normalized harness force (square root transformed) as the dependent variable and foot flight time as the predictor variable. The linear best-fit line for maintained contact foot flight time on normalized harness force is plotted. Earlier foot-rung contact times (less foot flight time) are associated with a contact slip outcome, but longer foot flight times for maintained foot contact outcomes are associated with high normalized harness forces. Thus, there may be an optimal time window to reestablish foot placement. Bold *p*-values on the graphs denote statistical significance.

Appendix C.4.12 Harness force by number of beneficial fall recovery factors

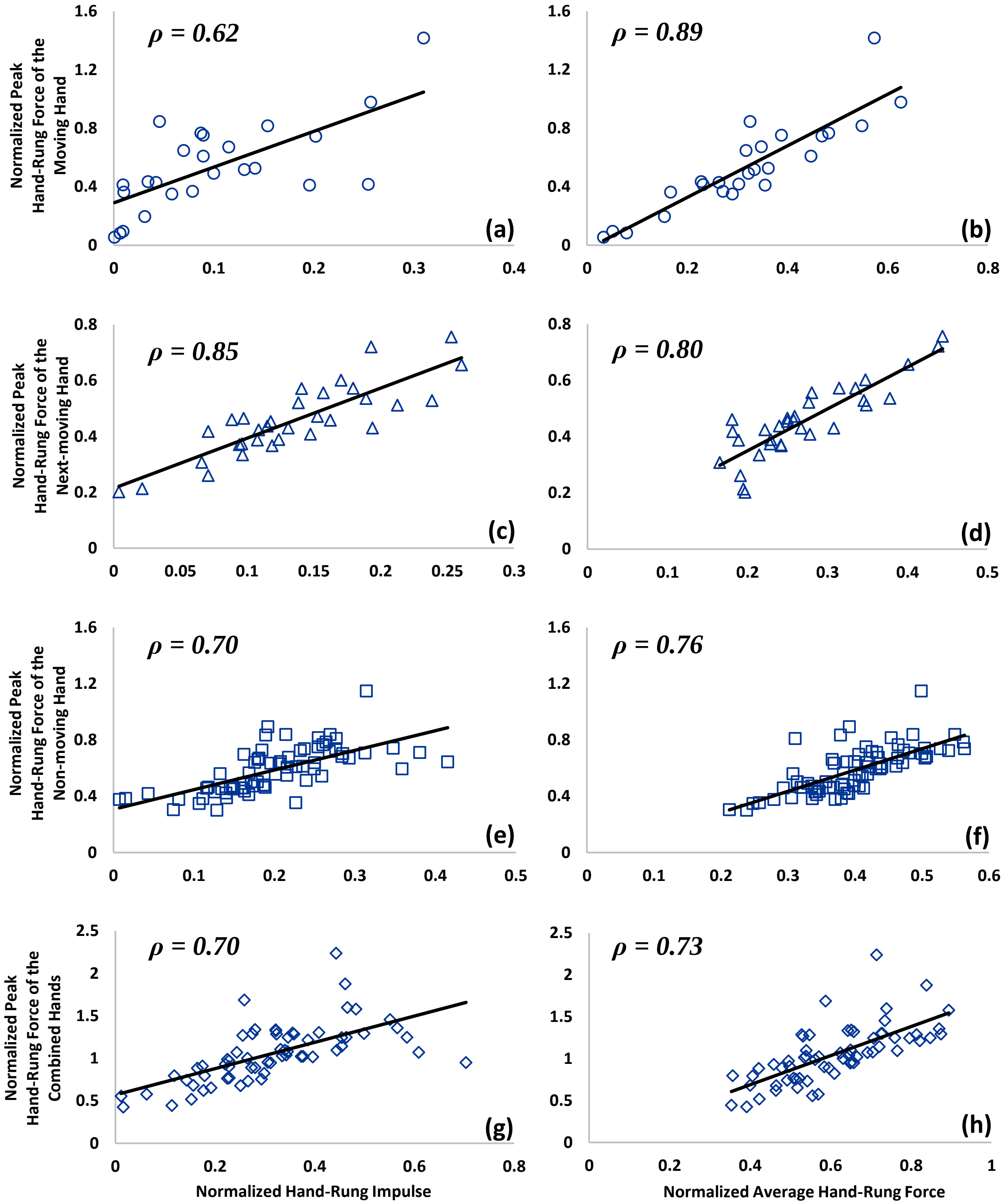


Appendix Figure 45: Harness force by beneficial fall recovery factors. Mean normalized harness force by the number of beneficial fall recovery factors after an ascending (a) and descending (b) perturbation. Beneficial fall recovery factors consisted of upper body strength greater than 50% body weight, and optimal hand placement and reestablished foot placement after a climbing perturbation. Optimal hand placement after an ascending perturbation was reestablished hand placement two rungs up from the original rung (HM2). Optimal hand placement after a descending perturbation was not moving the hand from the original rung (HM0). Participants with more beneficial fall recovery factors had a lower harness force (better recovery response), reducing the likelihood of a fall outcome. Positive error bars represent the standard deviation and negative error bars represent standard error.

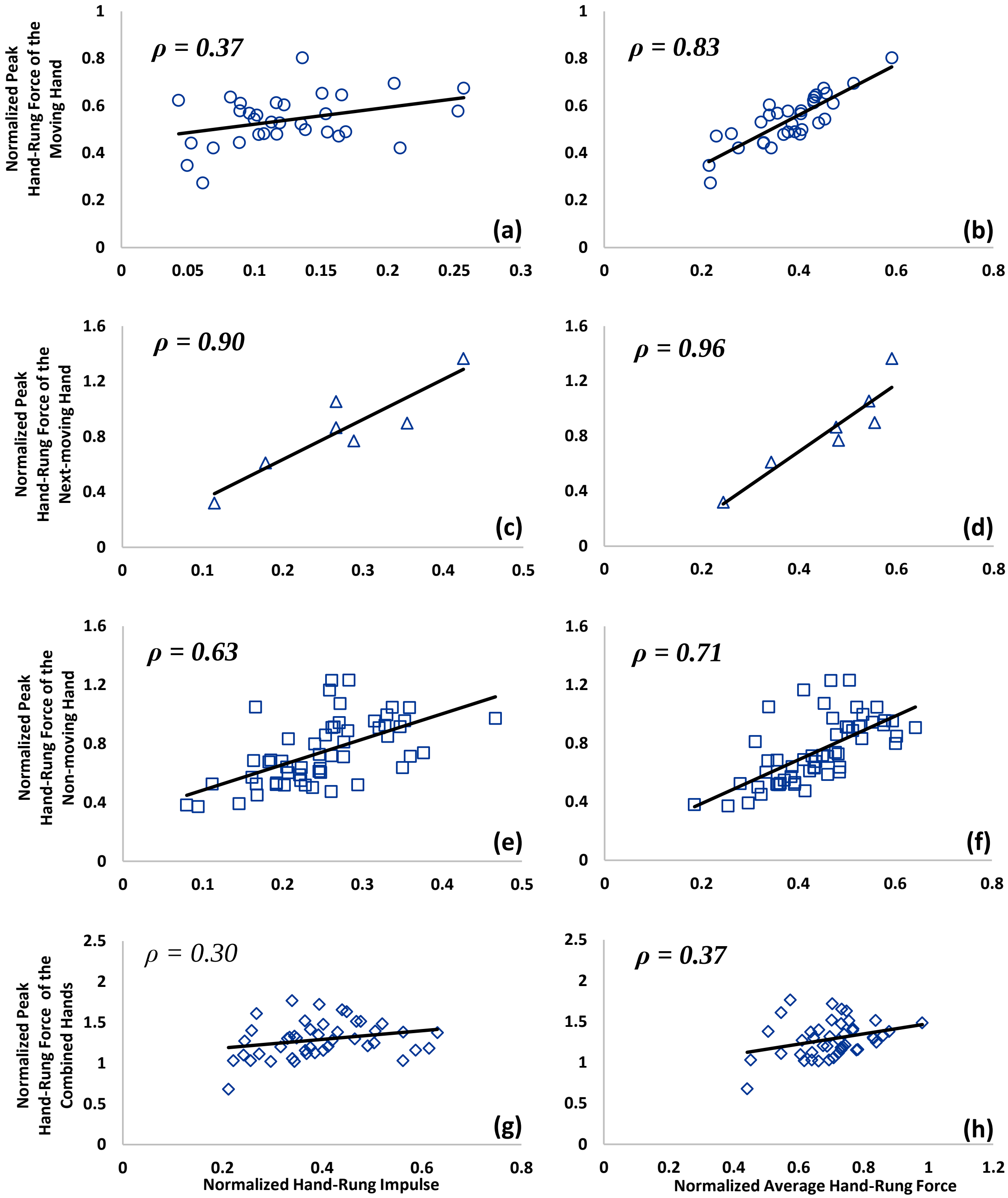
Appendix C.4.13 Correlations of peak hand-rung force with hand-rung impulse and average hand-rung force

Appendix Table 6: Correlations of peak hand-rung force with impulse and average hand-rung force. Pearson's correlations (*p*-value) of peak hand-rung force with hand-rung impulse and average hand-rung force after ascending (shaded) and descending (non-shaded) perturbations for the moving, next-moving, non-moving and combined hands. Bold values indicate correlations with a $p < 0.05$.

	Impulse	Average	Impulse	Average
Moving	**0.617 (0.001)**	**0.888 (<0.001)**	**0.372 (0.036)**	**0.828 (<0.001)**
Next-moving	**0.851 (<0.001)**	**0.802 (<0.001)**	**0.897 (0.006)**	**0.960 (<0.001)**
Non-moving	**0.700 (<0.001)**	**0.759 (<0.001)**	**0.633 (<0.001)**	**0.712 (<0.001)**
Combined	**0.701 (<0.001)**	**0.728 (<0.001)**	0.297 (0.050)	**0.371 (0.013)**



Appendix Figure 46: Hand-rung force peak across impulse and average after an ascending perturbation. Correlations between peak hand-rung force across hand-rung impulse (left side) and average hand-rung force (right side) for the moving (circles) (a, b), next-moving (triangles) (c, d), non-moving (squares) (e, f) and combined hands (diamonds) (g, h) (all values normalized). Bold correlations denote statistical significance.



Appendix Figure 47: Hand-rung force peak across impulse and average after a descending perturbation. Correlations between peak hand-rung force across hand-rung impulse (left side) and average hand-rung force (right side) for the moving (circles) (a, b), next-moving (triangles) (c, d), non-moving (squares) (e, f) and combined hands (diamonds) (g, h) (all values normalized). Bold correlations denote statistical significance.

Appendix D: Impact of Student-specific Content on Improving Student Engagement in a Biomechanics Outreach Program

Appendix D.1 Methodology

Appendix D.1.1 Questions asked to students in the interest forms

What is a job or career you’re interested in?

What are your favorite sports?

Do you have any favorite athletes? If yes, who?

Do you have a favorite video game? If yes, what?

What are other activities you enjoy?

Do you have any favorite celebrities? If yes, who?

Appendix D.1.2 Biomechanics quiz

1. Match the left and right sides by labeling the right side with the corresponding letter

a. Kinetics	___ Tension
b. Ligaments	___ Force = mass x acceleration
c. Bones	___ Describe motion with force
d. Kinematics	___ measures how fast velocity is changing
e. Newton's 2^{nd} Law	___ Describe motion without force
f. Pulling	___ Force / cross-sectional area
g. Stress	___ Provide support and protection
h. Accelerometer	___ Connect bone to bone

2. Calculate the force with the following equation and information:

   Force = stiffness x length change

   Stiffness = 6 pounds per inch
   Starting length = 2 inches
   Ending length = 7 inches

3. What are the functions of the musculoskeletal system?
   a. Production & Storage
   b. Movement
   c. Support & Protection
   d. b. and c.
   e. all of the above

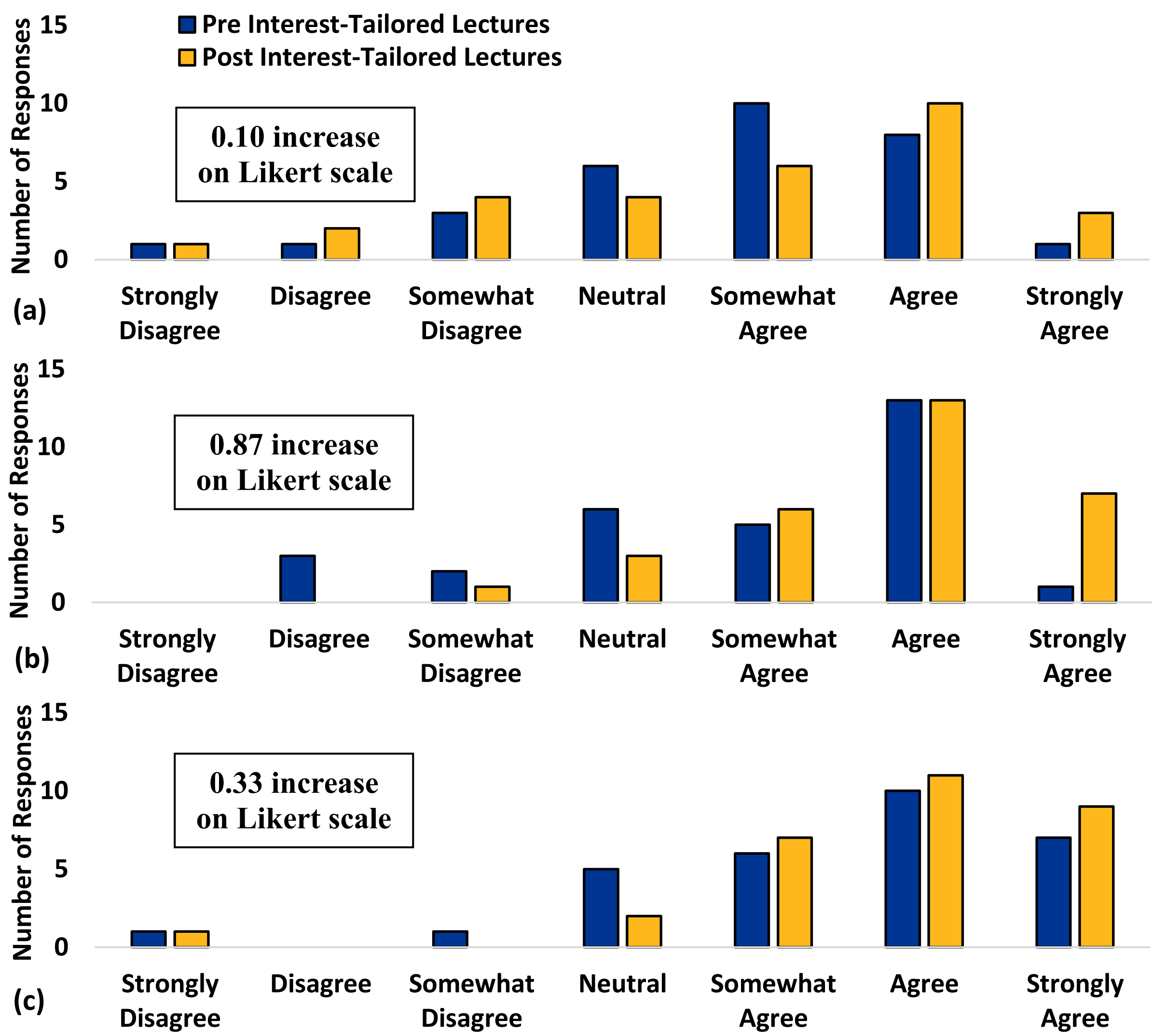
4. The processes of making data comparable is
   a. Calibration
   b. Electromyography
   c. Equaling
   d. Normalization
   e. None of the above

5. Name two uses of biomechanics.

6. Short essay: Explain the importance in applying biomechanics in one of the uses talked about this week.

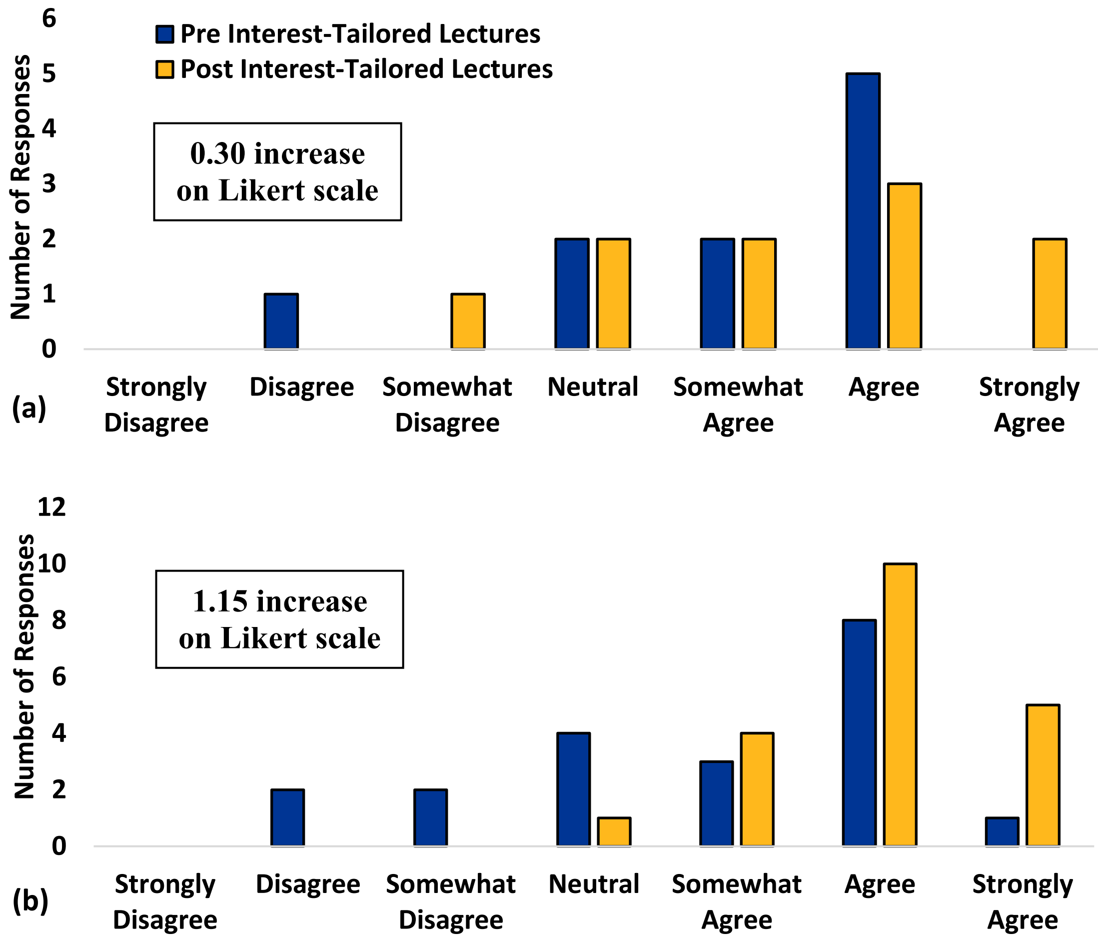
Appendix D.2 Supplementary Analyses

Appendix D.2.1 Responses by Likert rating per engagement question



Appendix Figure 48: Number of responses per engagement level. The number of student responses per agreement response (Likert score rating) for interest in biomechanics (a), engagement during lecture (b) and enjoyment in hands-on activities (c) pre (blue bars) and post (yellow bars) interest-tailored lectures. Boxes display the mean increase in engagement on the Likert scale from pre to post interest-tailored lectures.

Appendix D.2.2 Responses by Likert rating for engagement during lecture per male and female students



Appendix Figure 49: Number of responses for engagement during lecture by gender. The number of student responses per agreement response (Likert score rating) of engagement during lecture for male (a) and female (b) students pre (blue bars) and post (yellow bars) interest-tailored lectures. Boxes display the mean increase in engagement during lecture on the Likert scale from pre to post interest-tailored lectures.

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