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Individual, Occupational and Biomechanical Factors That Affect Slip and Fall Risk from Fixed Ladders

Erika Mae Pliner
University of Wisconsin-Milwaukee

INDIVIDUAL, OCCUPATIONAL AND BIOMECHANICAL FACTORS THAT AFFECT SLIP AND FALL RISK FROM FIXED LADDERS

by

Erika Mae Pliner

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ABSTRACT

INDIVIDUAL, OCCUPATIONAL AND BIOMECHANICAL FACTORS THAT AFFECT SLIP AND FALL RISK FROM FIXED LADDERS

by

Erika Mae Pliner

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Injuries from ladder falls are prevalent and severe. Previous research has examined certain elements of ladder falls such as the ladder base slipping, but few studies have examined the factors that contribute to climbers falling from the ladder, particularly for permanent/fixed ladders. In addition, the biomechanical response to a ladder slip/misstep during ladder climbing and the factors that affect a fall from a ladder are not well understood. This thesis is a two part study that simulated ladder slips and missteps in order to find factors 1) associated with ladder slip risk and 2) that decrease fall severity from a ladder. Specifically, 32 participants were recruited for study 1 to investigate restricted toe clearance, hand positioning, age, climbing direction and climbing biomechanics with slip risk. Thirty-five participants were recruited for study 2 to investigate the impacts of gender, climbing direction, gloves, and hand and foot responses on fall severity. Study 1 found restricted toe clearance, younger ladder climbers, and climbing biomechanics with greater variation to be associated with an increased slip risk. Study 2 found that males, ascending climbs, post-perturbation hand placements that extended the arm, and foot responses that hit the top of a ladder rung were associated with decreased fall severity.

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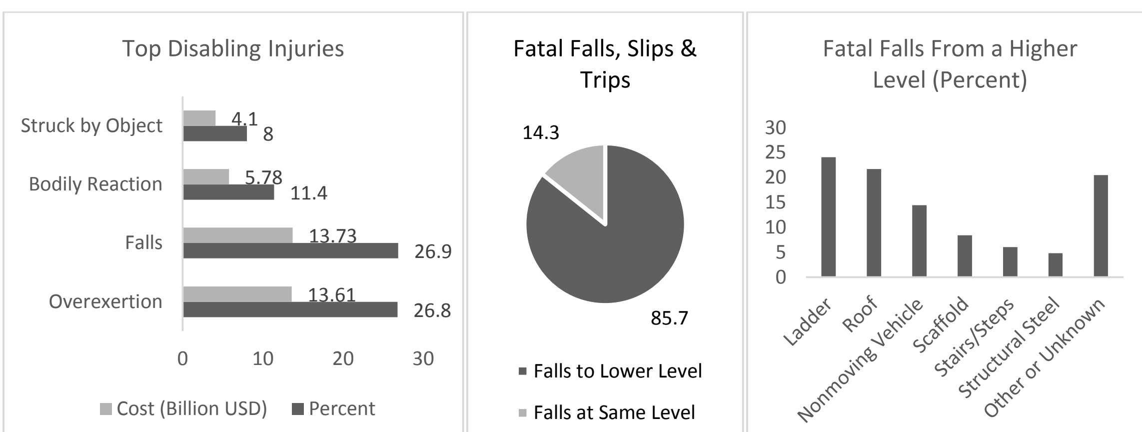
Chapter I

Introduction

1.1 Ladder Falling Epidemiology

Mortality rates due to falls increased by more than two-thirds from 2000 to 2009 (Rockett et al. 2012). Falls are the leading cause of disabling injuries, accounting for 27 percent and $13.7 billion of workers compensation costs (Liberty Mutual Research Institute 2012.b) (Figure 1.A). Eighty-six percent of fatal falls are to lower levels (Bureau of Labor Statistics 2012.b) (Figure 1.B), with the plurality of falls to lower levels involving a ladder (Bureau of Labor Statistics 2012.a) (Figure 1.C). Ladder fall injuries commonly result in fractures that lead to high compensation claims and more days away from work (Smith et al. 2006). Ladder falls also account for 8% of non-fatal falls (Webster 2000). In one year, falls to lower levels resulted in over 55,000 non-fatal injuries (Bureau of Labor Statistics 2013) and non-fatal ladder fall injuries resulted in a median 20 days away from work (Socias et al. 2014).



(A) (B) (C)

Figure 1: Statistics for falls: (A) percentage and workers compensation cost of top disabling injuries (Liberty Mutual Research Institute 2012.b); (B) percentage of fatal falls, slips and trips to lower level (Bureau of Labor Statistics, 2012.b); (C) percentage of fatal falls from a higher level (Bureau of Labor Statistics 2012.a).

Table 1: Previous Ladder Fall Research – Field based, Falls with ladders/climbing biomechanics, and Falls from ladders.

Authors	Experimental Design	Risk Factors Examined	Outcome Measures	Key Findings
Field based				
Gordon S. Smith, Robert A. Timmons, David A. Lombardi, Dheeresh K. Mamidi, Simon Matz, Theodore K. Courtney, and Melissa J. Perry; 2006 (Smith et al. 2006)	Retrospective Cohort	gender, age, task, body part injured, cause of fall, duration of disability, incurred medical costs, and industry	number of falls, fall fractures, non-fall fractures, proportionate injury rate, other ladder injuries, and expected fall fracture	Falls cause 89% of fractures and result in more medical costs and disability days than other injuries; 7% of ladder injuries were fracture related cases; common causes to ladder falls were instability (22%) and loose footing (22%)
Christina M. Socias, Cammie K. Chaumont Menendez, James W. Collins and Peter Simeonov; 2014 (Socias et al. 2014)	Retrospective Cohort	gender, age, race/ethnicity, employment status, establishment size, industry, occupation, part of body injured, disposition and fall height	number of falls, percentage, injury rate, and median days from work	Injuries from ladder falls are severe but can be prevented through safer ladder climbing practices; ladder falls can be prevented with reduced use of ladders, alternative equipment for elevated work, properly selected and thoroughly inspected ladders, and training information
Gareth W. Shepherd, Rodger J. Kahler, and Jean Cross; 2006 (Shepherd et al. 2006)	Retrospective Cohort	falls of people and electrocution	fall with ladder, fall from ladder, fall during transition to/from ladder, ladder contact with power lines, and climber contact with electricity	Falls of people account for 65% and electrocution accounted for 31% of ladder fatalities; multiple fatalities occurred from falls with ladder due to sliding of bottom/top support (15%), falls from ladder after overbalancing/slipping (12%), falls from ladder during on/off transition (14%), and falls from top of step ladder (3%)
H. Hsiao, P. Simeonov, T. Pizatella, N. Stout, V. McDougall, and J. Weeks; 2008 (Hsiao et al. 2008)	Meta-analysis	slip of ladder base, tipping of ladder top, persons tripped or slipped, and ladder structure failure	angle of ladder, coefficient of friction (COF) at ladder top and base, loads on the ladder, overreaching, transition on/off ladder, securing ladder top, carrying objects, struck by object, misstep, slips, age, ladder selection/conditions	Four actions to improve ladder safety: 1) visual indicators to assist in proper ladder setup angle 2) ease of ladder to surface transition 3) ladder accessories to ease carrying, assembling and storing of accessories 4) graphical guides for safe ladder use, maintenance and mechanical-flaw detection
Susan M. Moore, William L. Porter, and Patrick G. Dempsey; 2009 (Moore et al. 2009)	Retrospective Cohort	type of mine, nature of injury, body part injured, age, workdays lost, injury scenario, object in hand, method of injury, equipment involved, contributing factors, and environmental factors	number of falls and percentages	Fractures and sprains were the most common injuries to occur; nearly 50% of injuries occurred during the ingress/egress with the majority during egress; about 25% of the injuries occurred during the maintenance task
Laboratory Experiment-Falls with ladders/climbing biomechanics				
Wen-Ruey Chang, Chien-Chi Chang, Simon Matz, and Dan Ho Son; 2004 (Chang et al. 2004)	full-factorial repeated measures	climbing speed, body weight, ladder type, ladder angle, and friction at ladder top	normal and shear forces at ladder base and floor interface and required COF	The required COF at the ladder base increased 77% from a 75° to 65° angle; friction at ladder top and ladder type has minor effects on required COF at the ladder base
Wen-Ruey Chang, Chien-Chi Chang, and Simon Matz; 2005 (Chang et al. 2005)	full-factorial repeated measures	ladder shoe type, surface type, surface condition, moving speed, weight condition	available COF and slip probability	The available COF of the tested ladder shoes differed on oily surfaces; different climbing conditions can be supported by the available friction on dry surfaces, but slip potential is significantly increased on oily surfaces

T. J. Armstrong, J. Young, C. Woolley, J. Ashton-Miller, and H. Kim; 2009 (Armstrong et al. 2009)	full-factorial repeated measures	ladder pitch, ladder bank, rungs/siderails, climbing direction, and carrying toolbox	peak hand and foot forces	Lower limbs account for the majority of the work to climb a ladder; the hands must always exert force to prevent falling from a vertical ladder; require hand force is related to vertical hand placement and body center of mass; tilting the ladder forward reduces hand forces; tilting the later laterally did not significantly affect peak hand or foot forces
Donald S. Bloswick and Don B. Chaffin; 1990 (Bloswick and Chaffin 1990)	full-fractional repeated measures	rung separation, ladder slant, climbing direction, climbing velocity, time-into-cycle, and anthropometry	articulation moment, back compressive force, body link with acceleration, and hand and foot forces	Slipping is not a hazard for individuals with reasonable strength and mobility; grip strength may be exceeded if the individual experiences a foot slip; localized fatigue may occur at the elbow, hip and ankle joints during ladder climbing; certain ladder climbing activities may generate high back forces
Don B. Chaffin and Terrence J. Stobbe; 1979 (Chaffin and Stobbe 1979)	one-factor repeated measures	rung/step spacing, climbing direction, climbing speed, body weight, climbing experience	peak forces on rungs	Ladder climbing results in high dynamic loads on rungs/steps; expected peak loading onto the rungs/steps is 1.7 x body weight in the vertical direction and 0.4 x body weight in the horizontal direction; 12-inch rung spacing is recommended for fixed ladder designs
Peter Vi; 2008 (Vi 2008)	one-factor repeated measures	ladder type and safety systems	maximum volume oxygen intake, heart rate, points of contact, muscle activity, and personal preference	Energy expenditure and forearm force exertion was higher when climbing a fixed ladder than tilted portable ladder; 10% of climbers used 3-point contact climbing on the vertical ladder; 85% of participants preferred the safety locking clip and rail over the double lanyard with two snap hooks
Laboratory Experiment-Falls from ladders				
Ralph L. Barnett and Peter J. Poczynok; 2000 (Barnett and Poczynok 2000)	one-factor repeated measures	grip/time relationship and gloves	sliding friction, reaction time, max grip, and fall height	Subjects experienced uncontrolled falls with bare hands (29%) and gloved hands (52%); rung grasping will prevent climbers from falling after a loss of foot placement; the average time to reach maximum grip strength was 0.349 seconds
Pilwon Hur, Binal Motawar, and Na Jin Seo; 2012 (Hur et al. 2012)	full-factorial repeated measures	glove condition and handle shape	breakaway strength and COF	Breakaway strength increased with increasing COF; greater breakaway strength was obtained with a circular handle over a rectangular handle
Justin G. Young, Charles Woolley, Thomas J. Armstrong, and James A. Ashton-Miller; 2009 (Young et al. 2009)	full-factor repeated measures	gender, handle shape/orientation and jamer, arm positions, and friction	peak force, peak force/body weight, grip strength, and peak force/grip strength	Breakaway strength was greatest for the fixed horizontal cylinder; participants may only support their own body weight with one hand utilizing the fixed horizontal handhold
Pilwon Hur, Binal Motawar, and Na Jin Seo; 2014 (Hur et al. 2014)	one-factor repeated measures	glove condition and muscle groups	muscle reaction time, muscular effort over time, and handle displacement	Lower COF increased muscular effort and handle displacement; muscle reaction time was not affected by glove condition; the primary muscles to stabilize the perturbed handle were the forearm and latissimus dorsi

1.2 Previous Ladder Fall Research

Field based studies identified reoccurring causes of ladder falls and methods to improve ladder climbing safety. Ladder fall causes can be subdivide under two categories of ladder falls (Table 1). A person may experience a fall with a ladder or a fall from a ladder. A fall with a ladder is caused by the ladder slipping and the climber falling with the ladder. A fall from a ladder is caused by the climber losing coupling points (i.e. hands or feet) with the ladder and falling from the ladder. Falls with ladders are typically caused by ladder instability (Smith et al. 2009) that resulted in sliding of the ladder base or ladder top (Shepherd et al. 2006). Causes of most falls from ladders were from a person's overbalance, slip, and misstep (Shepherd et al. 2006). Forty-one percent of a person's overbalance, slip, or misstep on a ladder occurred during ladder ascent or descent (Shepherd et al. 2006). A field specific study in the mining industry found similar results with 50% of their injuries occurring while workers ingress or egress onto/from mining machinery (Moore et al. 2009). Outcomes from ladder falls were found to result in severe injuries although previous researchers have suggested that these injuries are preventable injuries (Socias et al. 2014). Socias et al. recommends five steps to prevent ladder fall injuries: 1) reducing or eliminating ladder use by applying safer environment designs to increase the amount of work at the ground level; 2) providing safer equipment for elevated work; 3) selecting well-maintained and appropriate ladders for the task at hand; 4) providing additional ladder accessories to increase safe ladder use; and 5) providing ladder safety information and training to employees.

Multiple laboratory studies have investigated falls with ladders and ladder climbing biomechanics (Table 1). Ladder setup angle and ladder shoe friction at the base of the ladder are two factors that were determined to affect slipping of a ladder (Chang et. al 2004; Chang et al. 2005). A 75 degree angle between the ground and ladder had a lower required coefficient of friction (COF) than a 65 degree angle, resulting in less risk of the ladder slipping and a safer ladder setup (Chang et al. 2004). Different ladder shoes varied in friction on oily surfaces, and an oily surface greatly increased the slip risk of ladders compared to a dry

surface (Chang et al. 2005). In addition, the ladder shoe with the highest friction had lower hardness and less surface contact than the other ladder shoes, which resulted in more pressure at the shoe to surface contact (Chang et al. 2005). Other studies measured forces during ladder climbing to explain ladder climbing biomechanics (Armstrong et al. 2009; Bloswick and Chaffin 1990; Chaffin and Strobbe 1979). Ladder climbing relies on the lower body to support the majority of the body's weight, but an additional force from the hands is required during vertical ladder climbing to prevent the climber from falling (Armstrong et al. 2009). The force applied by the hands may not be enough to support the climber if they were to lose footing while ladder climbing (Bloswick and Chaffin 1990). In addition, the hand and foot forces applied to the rungs will be increased with greater rung spacing (Chaffin and Strobbe 1979). Another study investigated energy expenditure and climbing style between vertical and slanted ladders (Vi 2008). More energy was required for vertical ladder climbing and very few utilized three-points of contact throughout the entire climbing cycle during vertical climbing (Vi 2008).

There are only a few laboratory studies that have investigated falls from ladders (Table 1). The majority of fall from ladder studies have focused on the ladder handle and hand interaction (Barnett and Poczynok 2000; Hur et al. 2012; Young et al. 2009; Hur et al. 2014). Gripping ladder rungs were predicted to serve as a better means to stop a ladder fall than ladder siderails (Barnett and Poczynok 2000). Two studies investigated handle orientation with "breakaway force" which is the peak force generated onto a handle by the hand before the handle breaks away from the individual's grasp (Hur et al. 2012; Young et al. 2009). These studies found the breakaway force to be greatest with the horizontal cylindrical handles (rung design). Friction was another factor that was investigated with handles (Hur et al. 2012; Young et al. 2009; Hur et al. 2014). Increased friction was found to increase the breakaway strength on the handle (Hur et al. 2012; Young et al. 2009) and less friction was associated with greater muscular effort and greater handle displacement to stabilize an upward moving handle (Hur et al. 2014).

Several gaps are present in the ladder fall literature of field based and laboratory experiments investigating falls with ladder, climbing biomechanics and falls from ladders. Field based studies illustrated ladder setup indicators and ladder accessories that may have potential for preventing common ladder fall events (Shepherd et al. 2006; Hsiao et al. 2008), but limited advice is given for proper ladder climbing training. Many laboratory experiment studies have focused on falls with ladders and ladder climbing biomechanics, but falls from ladders occur as often as falls with ladders (Shepherd et al. 2006) and climbing biomechanics that lead to a slip or misstep are unknown. Studies that have focused on falls from ladders have only considered the upper body interaction with the rung (Hur et al. 2012; Hur et al. 2014), which may be an oversimplification of falls from ladders.

1.3 Motivation and Purpose for Study 1: Effects of foot placement, hand positioning, age and climbing biodynamics on ladder slip outcomes

Slipping from fixed vertical ladders is a common cause of occupational injuries but is not well understood. More than half of falls from ladders occur from a person's overbalance, slip or misstep (Shepherd et al. 2006). Preventing the likelihood of a ladder slip will lower the probability of a ladder fall. Vertical ladder climbing primarily relies on the feet to support the body's weight and an applied force from the hands to prevent the climber from falling (Armstrong et al. 2009). An analysis of horizontal and vertical forces suggested foot forward slipping of ladder climbers if there is low friction between the feet and rungs (Bloswick and Chaffin 1990). Thus, existing epidemiological and biomechanics research supports that slipping from ladders is an important occupational hazard.

Factors that may affect ladder slip risk are restricted toe clearance, hand positioning, climbing direction, age, and climbing biomechanics. Since the feet support most of the body's weight during ladder climbing, having a sufficient clearance between the ladder and an anterior surface for the toe may be necessary to maintain a solid foot placement. Thus, toe clearance may be an important factor of slip risk.

To facilitate a solid foot placement, toe clearance regulations on fixed ladder insulations have been made by worker safety organizations (United States Occupational Safety Health Administration 2003; United States Mining Safety Health Administration 1985). However, there is a large difference between these two organization's toe clearance standards (OSHA: 180 mm vs. MSHA: 76 mm). The discrepancy between toe clearances may be due to the lack of knowledge on the effects of restricted toe clearance with ladder climbing. Restricted toe clearance may increase slip risk by placing the rung position closer to the base of support limit (i.e., the toe). Many studies have investigated ladder handle designs, spacing and orientations because the hands are thought to be a critical aspect of ladder climbing (Armstrong et al. 2009; Chaffin and Strobbe 1979; Barnett and Poczynok 2000; Hur et al. 2012; Young et al. 2009). Utilizing ladder rung hand position over ladder rail hand position has been predicted to provide a better means to prevent a ladder fall (Barnett and Poczynok 2000; Hur et al. 2012; Young et al. 2009) yet this effect has not been confirmed during actual ladder slipping events. Since slipping occurs before the fall, hand position may not affect ladder slip risk. Another factor that has not been investigated with slip risk is climbing direction. Ladder ascent and ladder descent can be argued to be two very different tasks. Ladder ascent uses energy to lift the body upward whereas ladder descent absorbs energy to lower the body. These different tasks may result in one task having a higher slipping risk than the other. Slip risk may be higher during ladder descent because more injuries are reported during ladder descent than ladder ascent (Moore et al. 2009). Age is another factor that is likely to affect slip risk since younger ladder climbers typically will, on average, have less climbing experience and older workers are known to be at greater injury risk (Mitchell 1988). Climbing biomechanics may also influence slipping risk since analogous research in same level slipping has suggested that walking biomechanics has a major impact on slip risk. When experiencing a slippery surface during walking tasks, cadence and step length were gait characteristics that were found to affect slip risk (Moyer et al. 2006). Also, foot and body positioning have been shown to impact fall risk and severity when experiencing a slip during sit-to-stand tasks (Pavol et al.

2004). Similar to gait characteristics that influence slip risk and body and foot positioning that influence fall risk, there may be climbing biomechanics that increase slip risk. Previous research has also suggested that climbing styles that increase the horizontal forces applied to ladder rung may be associated with slip risk (Bloswick and Chaffin 1990). Thus, specific climbing biomechanics that may affect slip risk are foot forces, climbing speed, body positioning and foot positioning. Identifying the impacts of restricted toe clearance, hand positioning, climbing direction, age, and climbing biomechanics on ladder slipping risk may be critical to develop interventions for reducing ladder slip and fall events.

1.4 Motivation and Purpose for Study 2: Ladder climbing factors that affect the severity of falls from ladders

In addition to preventing ladder slips, reducing the severity a fall from a ladder after a perturbation is experienced is also an opportunity for preventing ladder fall injuries. Stopping a ladder fall can be broken down into three time phases: 1) free fall; 2) climber's muscle reaction; and 3) deceleration (Barnett and Poczynok 2000). However, it is unclear how occupational or personal factors influence this recovery period and the resulting fall severity. Thus, understanding factors that affect fall severity may lead to methods to prevent fall from ladder injuries.

Factors that may affect the severity of fall from a ladder are gender, climbing direction, glove condition, and hand and foot responses. Gender differences including strength and anthropometry may lead to differences in fall severity. Increased upper body strength in male climbers (Miller et al. 1993) may result in males generating more force during the recovery and reducing their fall severity relative to female climbers. Other gender differences that may influence fall severity are arm length (Miller et al. 1993; Nicolay and Walker 2005), hand size (Nicolay and Walker 2005), height (Miller et al. 1993), and weight (Chau et al. 2004). Climbing direction is another factor that may influence fall severity. Falls during descent may be more difficult to stop than ascent because the body's downward momentum during

descent has a greater downward velocity than ascent at the start of fall. Also, previous research has determined that falls are more prevalent during ladder descent than ascent (Moore et al. 2009). Climbing equipment such as gloves may improve or reduce a climber's ability to stop a ladder fall. High friction gloves increase the force the hand can generate onto a rung before the rung is broken from one's grasp (Hur et al. 2012). This force at rung "breakaway" is assumed to be predictive of grasping capabilities during an actual ladder falling scenario (Hur et al. 2012). This increased force may reduce the time to decelerate the falling climber. Therefore, high friction gloves may reduce fall severity from a ladder. In addition, individual hand and feet responses during a ladder fall may affect fall severity. Three-points of contact (one hand and both feet or two hands and one foot) with the ladder are recommended for the majority of ladder climbing (United States Occupational Safety Health Administration 2003), but very few climb with three-points of contact during vertical ladder climbing (Vi 2008). More points of contact may increase the total force an individual is able to support during the deceleration phase. This increased load support capacity may improve one's ability to reduce fall severity, particularly if one is incapable of supporting their body weight with one hand. Since the number of contact points after a perturbation depend on hand and feet responses to the perturbation, there may be specific responses that provide a better means to reduce fall severity from a ladder. Thus, identifying the impacts of gender, climbing direction, gloves, and hand and feet responses during a ladder fall is important to decreasing severity of falls from ladders.

1.5 Goals and Hypotheses

This thesis describes two studies that are related to slip and fall risk from ladders. Study 1 focuses on the factors that are associated with slipping during ladder climbing whereas Study 2 focuses on the factors that affect the severity of fall from a ladder. Each study has a set of goals with corresponding hypotheses.

Study 1

Goal 1: To determine the effects of restricted toe clearance, hand positioning, and climbing direction on slip outcomes.

Hypothesis 1.1: Restricted toe clearance will increase the probability of slip.

Hypothesis 1.2: Hand positioning will not affect slip outcome.

Hypothesis 1.3: Slip rate will be higher with descending than with ascending climbs.

Goal 2: To determine the effects of age on slip outcomes.

Hypothesis 2: Age will affect an individual's slip risk.

Goal 3: To identify climbing biomechanics that are associated with lower ladder slipping risk.

Hypothesis 3: Ladder climbing biodynamics such as foot forces, climbing speed, body positioning and foot positioning will be different between participants who slipped versus those who did not slip.

Study 2

Goal 1: To determine personal and occupational factors that affect the severity of a fall from a ladder.

Hypothesis 1.1: Female ladder climbers will have a more severe fall following a perturbation than their male counterparts.

Hypothesis 1.2: Falls during ladder descent will result in a more severe fall outcome compared to ladder ascent.

Hypothesis 1.3: Falls with high friction gloves will result in a less severe fall outcome compared to bare hand and low friction glove conditions.

Goal 2: To identify recovery responses that decrease the severity of a fall from a ladder.

Hypothesis 2.1: Different hand placements following the perturbation will affect fall severity.

Hypothesis 2.2: Different foot placements following the perturbation will affect fall severity.

Chapter II

Study 1: Effect of foot placement, hand positioning, age and climbing biodynamics on ladder slip outcomes

This chapter was reproduced from the manuscript titled: "Effect of foot placement, hand position, age and climbing biodynamics on ladder slip outcome" in Ergonomics, 2014. Copyright permission was obtained to reprint this chapter (Appendix A).

2.1 Introduction

Ladder falls are a frequent cause of occupational injuries. In 2011, falls to lower levels caused 12% of fatal work injuries (Bureau of Labor Statistics 2012.b) and ladder falls were the second leading cause in falls to lower levels (Webster 2000). Over 50% of fall injuries experienced from mining equipment, which often require use of a ladder to ingress/egress, result in a fracture or sprain (Moore et al. 2009). The third largest causality insurance provider in the U.S. reported that workers' compensation costs for falls to lower levels were $5.12 billion in 2010 (Liberty Mutual Research Institute for Safety 2012.a). In a study surveying ladder fall fractures in 2000, 48% of these injuries resulted in $5000 or more in medical cost with 56% disabling the climber for 28 or more days (Smith et al. 2006). The high frequency, cost and amount of work days lost due to ladder falls indicates a serious need to investigate how ladder design and climbing techniques influence falling risk.

Ladder falls can be broadly categorized into falls from ladders and falls with ladders. Falls from ladders typically occur due to decoupling of the hand and/or foot with the ladder (Smith et al. 2006; Partridge et al. 1998; Hsiao et al. 2008; Shepherd et al. 2006). Falls with ladders typically occur due to the ladder tipping over, falling away from a wall or collapsing due to excessive reaching or improper ladder placement (Partridge et al. 1998; Smith et al. 2006). Previous research on ladder falling has primarily

focused on ladder set-up and the risk of the ladder tipping away from the wall or the feet slipping against the ground in an effort to prevent falls with ladders (Chang et al. 2005). Few studies have investigated the beginnings to falls *from* ladders (Hsiao et al. 2008). This gap in the literature is surprising given that falls from ladders are the most common reason for ladder-related fractures (Smith et al. 2006). The most common initiating event for a fall from a ladder is due to a person's overbalance, slip or misstep (Shepherd et al. 2006). Slipping occurs when the friction between the shoe and rung is inadequate to support climbing (Chang et al. 2005; Shepherd et al. 2006), however little is known about what other factors influence slipping risk.

The feet are the primary load-bearing interface during ladder climbing, while the hands are largely responsible for balancing the body during climbing and for recovery. Foot forces during climbing have been measured to be between 55% (Bloswick and Chaffin 1990) and 96% (Armstrong et al. 2009) of a climber's body weight. Bloswick & Chaffin suggest that low friction between the rungs and the feet may cause forward slipping of the foot based on analysis of horizontal and vertical forces. However, this conclusion was based on just the kinetics of climbing and did not simulate slipping. In order to maintain a solid footing surface during ladder climbing, the U.S. Mining Safety and Health Administration (MSHA) requires that ladders be placed at least 76 mm away from other surfaces (United States Mining Safety Health Administration 1985), while the Occupational Safety and Health Administration (OSHA) requires a 180 mm clearance. Exceptions to the OSHA rule include ladders in elevator pits and certain ladders in marine terminals, which require 100 to 110 mm of clearance (United States Occupational Safety Health Administration 2003). These conflicting toe clearance rules suggest that an understanding on the effects of restricted toe clearance on slip risk is needed to assess the appropriateness of the different guidelines. When using a ladder, climbers must choose between grasping the vertical rails of the ladder or the rungs of the ladder. A slip or misstep can manifest into a fall event if the hand decouples from the ladder after the perturbation. Previous research has suggested that grasping the rungs may provide a better grip than

grasping the rails (Armstrong et al. 2009; Barnett and Poczynck 2000; Young et al. 2009). Yet the effects of different hand grasping strategies on the risk of a slip have not been thoroughly examined. Determining if hand positioning affects slip risk is necessary to determine proper ladder climbing training. Lastly, previous evidence has suggested that a higher injury rate occurs while workers are egressing than ingressing of mining equipment (Moore et al. 2009), suggesting that workers might be at greater risk of slipping during ladder descent than ascent. Yet, no controlled study has been performed to consider the effect of ascent versus descent on slip risk. This study aims to identify the effects of foot positioning, hand positioning and ascent versus descent on slip outcomes in order to better inform safer climbing.

Age may be another significant factor in ladder slip outcomes since slip and fall incidents increase with age. Non-fatal lower-level falls show an uneven trend among working adults. The incidence rates of non-fatal lower level falls per 10,000 full time workers initially decreases with age from 4.9 in adults 20-24 to 4.2 for adults 25-34 and then increases to over 6 for adults over 45 years (Bureau of Labor Statistics 2013). Over the years many studies investigated the possible reasons for aging as a factor in level walking falls. In view of the evidence that postural coordination differs in some fundamental ways among younger and older adults (Strang et al. 2012), it can be argued that the underlying mechanisms of falling, as well as recovery, would also differ with age. Age-related level walking falls were largely linked to various health related issues, including diminished psychological and physiological functions (Blake et al. 1988; Gehlsen and Whaley 1990; Lord 2007; Barrett et al. 2010; Terroso et al. 2013). In 2008 Maki and colleagues summarized several methodologies aimed at reducing risk of falling related to aging (Maki et al. 2008). Among various interventions described in the study, balance-enhancing footwear and handrails were identified to be crucial for the preventions of falls. In spite of the lack of fundamental studies specific to ladder falls, it can still be argued that the relationship between falls and age found for level walking can hold for ladder falls. If so, identifying the possible underling reasons for age-specific ladder falls may be important.

Furthermore, the effects of other factors like climbing forces, climbing speed, body positioning and foot positioning on slipping risk are relatively unknown. Previous studies that have initiated an unexpected slip during level walking have found that gait characteristics such as cadence, step length and ankle dorsiflexion influence slip risk (Moyer et al. 2006; Marigold et al. 2003). Simulating ladder slips may reveal that similar critical variables influence slip risk on ladders, which may be useful to reducing ladder falls.

The first purpose of this study is to quantify the effects of restricted toe clearance, hand positioning, climbing direction and age on slip outcomes. The second purpose of this study is to quantify the differences in climbing biodynamics between participants who slipped versus participants who did not slip. In our study we developed the following hypotheses: H1.1: Restricted toe clearance will increase the probability of slip. H1.2: Hand positioning will not affect slip outcome. H1.3: Slip rate will be higher with descending than with ascending climbs. H2: Age will affect an individual's slip risk. H3: Ladder climbing biodynamics such as foot forces, climbing speed, body positioning and foot positioning will be different between participants who slipped versus those who did not slip.

2.2 Materials & Methods

2.2.1. *Subjects*

In this study, 32 (10 female) experienced ladder climbers volunteered to participate. Participants were recruited from demographics exposed to frequent ladder usage, such as firefighters, roofers, painters, construction works and divers. To qualify, participants needed to respond yes to a question that asked if they "regularly used ladders". The participants were separated into three age groups 18-24 yrs. (19.5 ± 2.0 yrs., 76.8 ± 17.0 kg, 1.7 ± 0.1 m), 25-44 yrs. (39.4 ± 4.5 yrs., 83.9 ± 9.8 kg, 1.8 ± 0.1 m) and 45-64 yrs. (53.3 ± 5.6 yrs., 87.8 ± 14.9 kg, 1.7 ± 0.1 m) (Table 2). Body mass increased as subjects' age increased ($p < 0.01$). The Bureau of Labor Statistics reports incident rates for workers who fall into the following age

categories: 16-19 years, 20-24 years, 25-34 years, 35-44 years, 45-54 years and 55-64 years (Bureau of Labor Statistics 2013). Therefore, each of the age ranges used in this study approximately corresponds to two age groups spanning 18 years to 64 years. The protocol was approved by the University of Wisconsin-Milwaukee Institutional Review Board (Protocol Number: 11.395). Participants underwent phone screening to confirm eligibility. Exclusion criteria included musculoskeletal and neurological disorders, pregnancy and balance disorders. Written informed consent was obtained prior to testing.

Table 2: Study 1 subject distribution amongst age groups with the mean ± standard deviation of age, body mass and height for each age group.

Age group	18-24 yrs.	25-44 yrs.	45-64 yrs.
Number of subjects (female)	11 (5)	12 (3)	9 (2)
Age (yrs.)	19.5 ± 2.0	39.4 ± 4.5	53.3 ± 5.6
Body mass (kg)	76.8 ± 17.0	83.9 ± 9.8	87.8 ± 14.9
Height (m)	1.7 ± 0.1	1.8 ± 0.1	1.7 ± 0.1

2.2.2 *Experimental Approach*

Participant's body mass, height and foot length were measured. Foot length was the distance from the most anterior point of the 1st toe to the posterior edge of the calcaneus. All participants were equipped with standardized attire, footwear and a safety harness. The footwear was a standard work shoe with a rubber sole and a raised heel. Forty-six reflective markers were placed on anatomical landmarks of the participant (Appendix B) and were tracked by 13 motion capture cameras at a frequency of 100 Hz (Motion Analysis Raptor Corp., Santa Rosa, CA) (Appendix C). Five reflective markers were placed on the outside of the rails between the 5th and 6th rungs of a vertical 12-foot industrial-use ladder that was secured in the middle of the motion capture volume (Figure 2). The markers placed on the ladder allowed for determination of how the person was moving relative to the ladder. The rung and rail spacing

on the ladder was within OSHA standards, spaced 279.4 mm and 463.6 mm apart, respectively (United States Occupational Safety Health Administration 2003). All rungs, except for the fourth rung, were equipped with strain gauges. The fourth rung (slip rung) on the ladder was replaced with a rod and lockable bearings. The bearings were locked for non-slip trials and were unlocked for slip trials so that the rung could spin freely. The spinning, low friction rung was used to induce slips during the perturbation trials. The bearings were hid from participants' view with wood covers. At the bottom of the ladder was an impact mat and the participant had a spotter and a belayer throughout the ladder climbing trials to ensure their safety.

Figure 2: Study 1 ladder climbing setup. The ellipse encircles the slip rung.

Participants were randomly assigned to two out of four different controlled climbing styles. Controlled climbing styles included two hand positions (rungs or rails) and two foot placement conditions (unrestricted or restricted toe clearance) (Figure 3). During trials where participants were assigned to

restricted toe clearance climbing, a board was placed at a distance of 25% of the participant's foot length anterior to the ladder. This distance approximates the minimum requirements of MSHA (76 mm) since the average foot length for participants in this study was 262 mm. Participants climbed the ladder several times prior to data collection so that they became comfortable with climbing the ladder used in this study. In all trials, participants were instructed to climb the ladder at a "comfortable but urgent pace" in order to simulate the speed a person would climb a ladder during a regularly-busy workday. For both of the controlled climbing styles, participants climbed the ladder 5-8 times with the spin rung locked in place and then once when the spin rung could freely spin. This exposed the participant to a low friction rung on both the ascent and descent during the slip trials. Therefore each participant was subjected to the low friction rung four times over the entire testing session. Between each trial the participants performed a walking task outside the lab so that they were not aware of the spin rung's locked/unlocked configuration.

(A) (B) (C) (D)

Figure 3: Controlled climbing strategies: (A) Rungs (B) Rails (C) Restricted toe gap (D) Unrestricted foot

Slipping outcomes were classified based on the kinematics of a marker placed on the subjects' toes. A trial was considered to be a slip if the foot completely slipped off of the spin rung. Slipping completely off of the rung was determined by the vertical position of the toe relative to the spin rung. If the toe moved posteriorly of the rung and to a lower height than the rung before the contralateral foot had made contact with the next rung, then the trial was classified as a slip. No slipping trials were observed where the subject's foot slipped forward and off of the rung so criteria was not developed for this type of

slip. For each slip event, the ascending and descending climbs were considered separately. If a slip was identified during ascent, the descent data was excluded from the analysis since subjects were aware of the rung's slippery condition.

Climbing biodynamics were characterized with climbing speed, double support time, foot forces and body and foot positioning. The foot force variables included the peak horizontal forces, peak vertical forces and the ratio between the peak horizontal and vertical forces. The body/foot positioning variables included the body angle with respect to the ladder, the angle of the foot relative to horizontal and the anterior/posterior positioning of the foot relative to the rungs. All of these variables were calculated using the baseline unperturbed climbing trial that preceded the perturbed (induced slip trial) to ensure that they were related to an individual's climbing style and were not influenced by the slip itself.

Climbing speed and foot forces were measured using the rung force data. To calculate the average climbing speed, the distance between the third and fifth rung was divided by the time it took to get between these two rungs. Specifically, the time from foot contact of the third rung to foot contact of the fifth rung was calculated using the rung force data. The timing of foot contact was determined as the first time point when foot forces began to exceed baseline plus 3 standard deviations of the vertical force. The timing of contralateral foot off was determined as the first time point when foot forces fell below the baseline plus 3 standard deviations of the vertical force. The horizontal and vertical foot forces were found from the peak force of rungs two, three and five and averaged across these three rungs. The foot forces were normalized to body mass. The force ratio of the feet was determined from the horizontal and vertical foot force to determine if this variable is relevant to slipping as suggested by Bloswick and Chaffin (Bloswick and Chaffin 1990).

Kinematic variables of interest consisted of the angle of the body, angle of the foot and anterior/posterior position of the foot. Each kinematic variable was parameterized at the time of foot

contact (FC) with the slip rung, contralateral foot off (CFO) following FC with the slip rung during the trial preceding the slip trial. The change (Δ) in these variables between foot contact and contralateral foot off was also calculated. Thus, the kinematic parameters measured were: body angle at FC (θ^{FC}_{body}), body angle at CFO (θ^{CFO}_{body}), change in body angle between FC and CFO ($\Delta\theta_{body}$), foot angle at FC (θ^{FC}_{foot}), foot angle at CFO (θ^{CFO}_{foot}), change in foot angle between FC and CFO ($\Delta\theta_{foot}$), foot placement at FC (d^{FC}), foot placement at CFO (d^{CFO}), and the change in foot placement between FC and CFO (Δd). Body angle was measured to represent how close the climber positioned themselves to the ladder. This angle has been demonstrated to be important for stability during other dynamic tasks such as sit to stand (Pavol, Runtz, and Pai 2004) and slipping (Bhatt et al. 2006). The body angle was measured between the vertical of the ladder and the line segment between the subject's toe marker and center of trunk (Figure 4.A). The center of trunk was found using anthropometric tables based on the cervical marker and mid-hip joint centers (De Leva 1996). The mid-hip joint centers were found using Bell's Method and the ASIS and PSIS markers (Bell et al. 1990) (Appendix D). Foot angle and foot placement were variables of interest since slipping occurs at the feet. The foot angle was calculated as the angle between the horizontal plane and a vector from the calcaneus marker to a marker placed anterior to the first toe markers (Figure 4.B). The foot placement was calculated as the anterior/posterior distance (y-direction, Figure 4.C) from the marker placed on the most anterior position of the first toe and the midpoint of the ladder rungs. Foot placement was normalized to participants' foot length. The timing of FC and CFO for kinematic parameters was determined using the anterior/posterior (y-direction) and superior/inferior position (z-direction) of the toe marker. Position data was used instead of force data since forces were not available on the slipping rung. For ascending climbs, the frames were found when the toe marker's superior/inferior position had a change greater than two standard deviations (2SD) of the average z-position during stance on the rung. FC was the first time point that the toe marker of the foot in contact with the fourth rung fell within this 2SD window. CFO was the last time point that the toe marker of the foot contralateral to the FC foot fell within the 2SD

window. For descending climbs, the same method was used, except the anterior/posterior position of the toe marker was used instead of the superior/inferior position. Visual inspection showed that these criteria accurately identified the moments of FC and CFO. The double support time was measured as the time difference between FC and CFO.

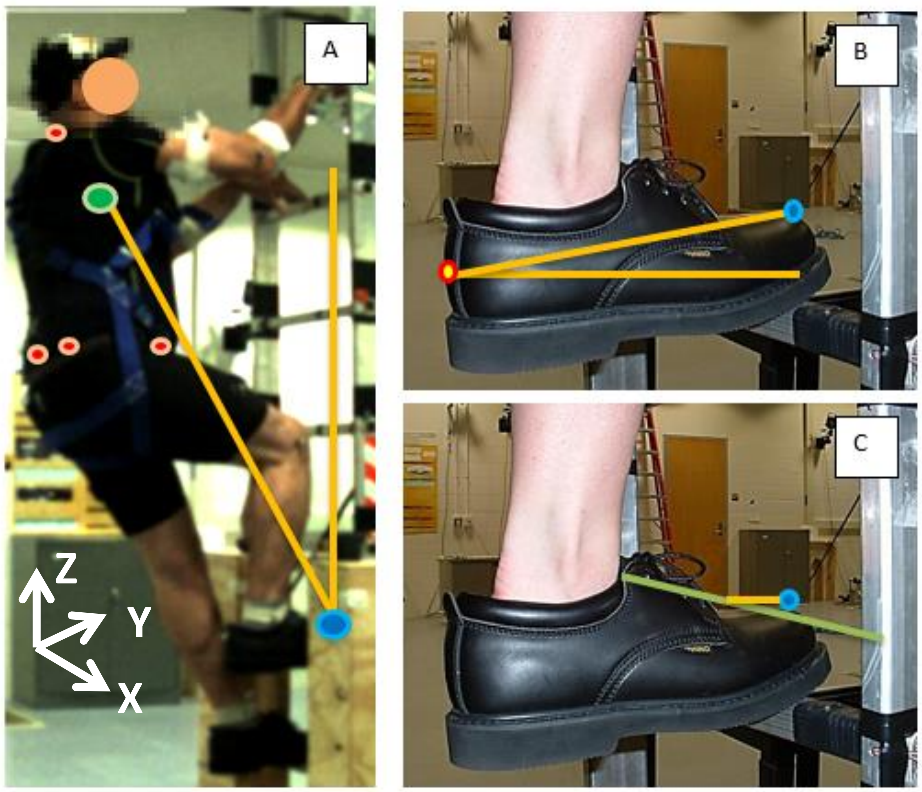


Figure 4: Measurements of body parameters: (A) Body Angle (B) Foot Angle (C) Foot Placement.

Fisher's exact test was used to evaluate hypotheses related to slip risk (Hypotheses 1 and 2), while ANOVA methods were used to identify significant differences between climbing biodynamics that led to a slip and those that did not lead to a slip (Hypothesis 3). Fischer's exact test was performed on the perturbed trials with slip outcome as the dependent variable and toe gap restriction, hand positioning, climbing direction and age group as the independent variables. Hypothesis 1.1 would be confirmed if restricted toe clearance was found to statistically affect slip rate. Hypothesis 1.2 would be confirmed if

hand positioning was found to not statistically affect slip rate. Hypothesis 1.3 would be confirmed if significantly more slips were observed during descent than ascent. Hypothesis 2 would be confirmed if age group was found to significantly influence slip rate. ANOVA analyses were performed separately for ascending and descending climbs with the climbing biodynamic variables (foot forces, climbing speed, double support time, body positioning and foot positioning) as the dependent variables and slip outcome as the independent variable. Age group was also included as an independent variable in this analysis to control for differences across age groups. Hypothesis 3 would be confirmed if climbing biodynamics were found to be statistically different in trials that led to slips compared with trials that did not lead to slips. Because only one slip occurred when toe clearance was unrestricted, only data from restricted toe clearance trials were included when testing Hypothesis 3.

2.3 Results

Participants slipped off of the rung 14 times during the 57 trials where they experienced a low-friction rung. Twelve participants experienced at least one slip. Seven slips occurred during ascent and seven slips occurred during descent. Nine slips were with rail hand positioning and five slips were with rung hand positioning. Slipping was over six times more likely with restricted than unrestricted toe clearance ($p < 0.01$) (Figure 5) confirming H1.1. Slip outcomes were not significantly influenced by hand positioning ($p = 0.31$)(Figure 5) nor climbing direction ($p = 0.51$) confirming H1.2 but rejecting H1.3. Age group significantly influenced slipping risk ($p < 0.01$) confirming Hypothesis 2 with slips occurring most frequently in the youngest age group (18-24 yrs.) (20.0%), followed by the eldest group (45-64 yrs.) (13.3%). No slips were observed in the middle group (25-44 yrs.) (Figure 5).

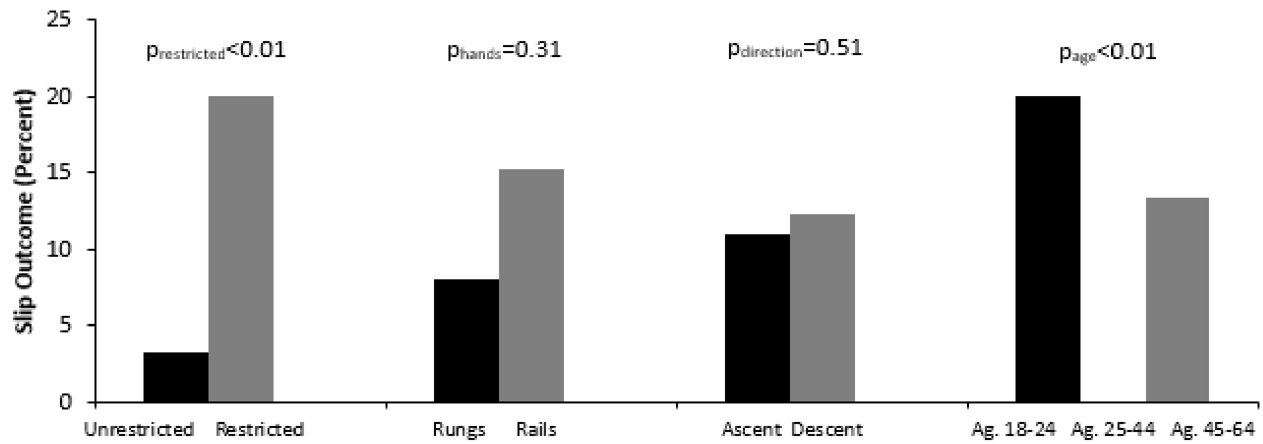


Figure 5: Effects of toe gap restriction, hand positioning, climbing direction and age group on risk of slipping. Numbers represent the percentage of exposures to the slippery rung that led to the foot slipping off of the rung.

Some of the climbing biodynamics variables were significantly different between trials that led to slips compared to those that did not lead to a slip, partially confirming Hypothesis 3. The foot angle at contralateral foot off (θ^{CFO}_{foot}, $p < 0.05$) was larger in trials leading to a slip than trials not leading to a slip when ascending the ladder (Figures 6 & 7, Table 3). Biodynamics that led to a slip during descent were characterized by a longer double support time ($p < 0.05$), a smaller body angle during foot contact (θ^{FC}_{body}, $p < 0.05$), greater change in body angle ($\Delta\theta_{body}$, $p < 0.05$) and a larger change in foot angle ($\Delta\theta_{foot}$, $p < 0.05$) (Figures 6 & 7, Table 3). Body angle at foot contact was smaller in the youngest age group than the other two age groups (θ^{FC}_{body}, $p < 0.05$) (Table 3). None of the other biodynamic variables were statistically significant.

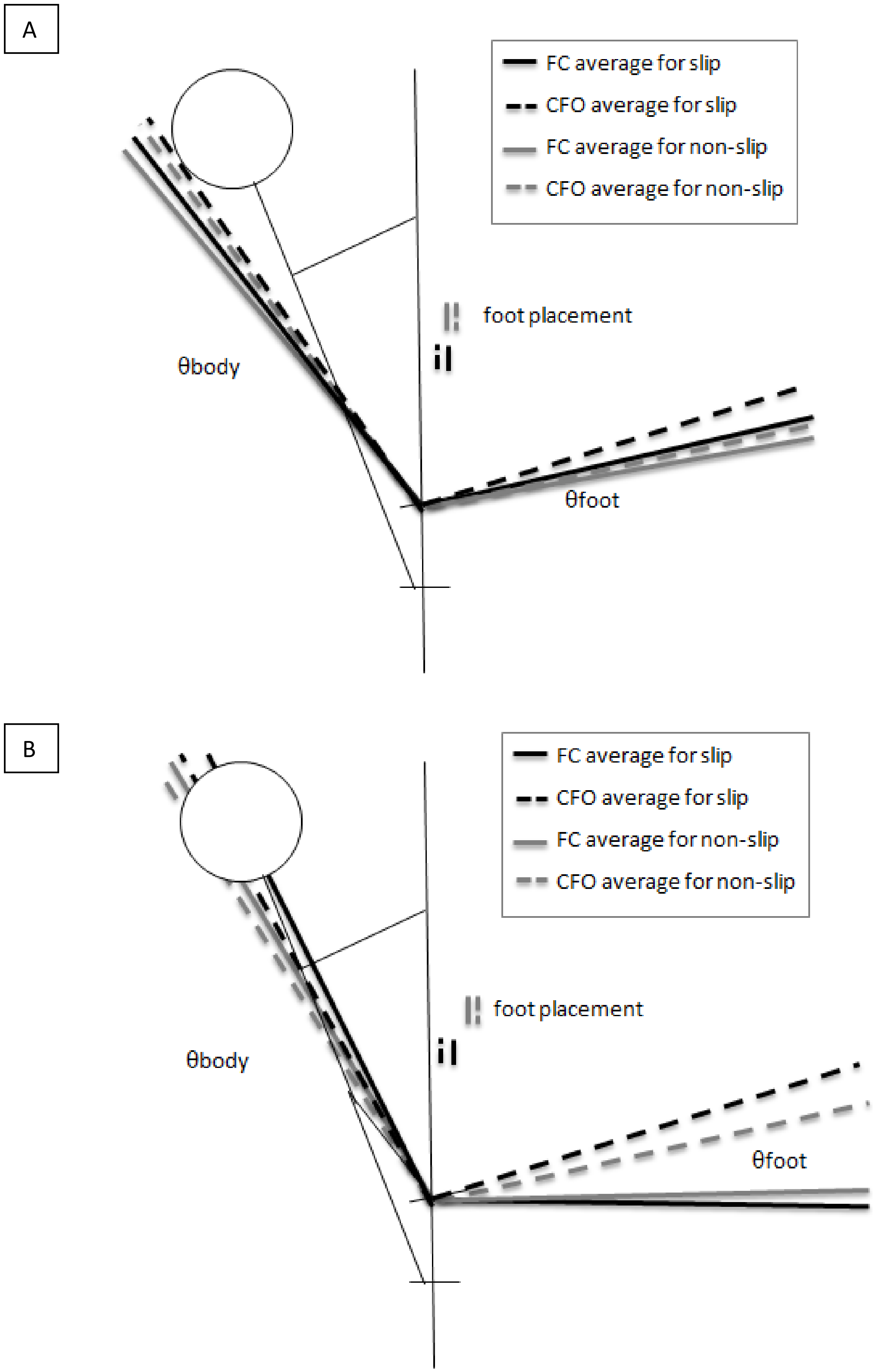


Figure 6: Average body angle (θ_{body}), foot angle (θ_{foot}) and foot placement for slip (black lines) and non-slip (grey lines) climbs at FC (solid lines) and CFO (dashed lines) during (A) ascent and (B) descent.

Table 3: Mean (standard deviation) (A) ascending and (B) descending biomechanical parameters during restricted foot placement.

A)

	Slip	No Slip	Aged 18-24	Aged 25-44	Aged 45-64
Speed (m/s)	0.51(0.08)	0.53(0.03)	0.53(0.05)	0.58(0.07)	0.48(0.06)
Double support time (s)	0.17(0.00)	0.17(0.00)	0.17(0.00)	0.18(0.00)	0.17(0.00)
θ^{FC}_{body} (°)	37.14(1.68)	37.28(0.66)	35.42(1.02)^{X}	38.47(1.52)^{X}	38.43(1.25)^{X}
θ^{CFO}_{body} (°)	34.58(1.78)	35.30(0.70)	33.31(1.08)	36.49(1.61)	36.36(1.32)
$\Delta\theta_{body}$ (°)	-2.56(0.57)	-1.98(0.22)	-2.11(0.35)	-1.98(0.52)	-2.07(0.43)
θ^{FC}_{foot} (°)	11.85(3.37)	9.29(1.32)	8.92(2.04)	9.95(3.04)	10.33(2.50)
θ^{CFO}_{foot} (°)	16.89(3.48)*	11.12(1.36)*	10.32(2.11)	13.70(3.14)	12.67(2.58)
$\Delta\theta_{foot}$ (°)	5.03(2.43)	1.82(0.95)	1.40(1.47)	3.75(2.20)	2.34(1.81)
d^{FC}_{NORM}	0.22(0.03)	0.22(0.01)	0.22(0.02)	0.22(0.02)	0.21(0.02)
d^{CFO}_{NORM}	0.21(0.03)	0.23(0.01)	0.24(0.02)	0.22(0.02)	0.22(0.02)
Δd_{NORM}	-0.01(0.02)	0.01(0.01)	0.02(0.01)	-0.01(0.02)	0.01(0.01)
VF	0.95(0.07)	0.99(0.03)	1.04(0.04)	0.93(0.06)	0.94(0.06)
HF	0.46(0.04)	0.48(0.02)	0.49(0.03)	0.45(0.4)	0.48(0.03)
FR	0.49(0.04)	0.49(0.02)	0.48(0.03)	0.49(0.04)	0.51(0.03)

B)

	Slip	No Slip	Aged 18-24	Aged 25-44	Aged 45-64
Speed (m/s)	0.43(0.06)	0.41(0.03)	0.42(0.05)	0.42(0.07)	0.40(0.05)
Double support time (s)	0.29(0.05)*	0.18(0.02)*	0.23(0.04)	0.20(0.07)	0.20(0.04)
θ^{FC}_{body} (°)	25.55(1.00)*	29.01(0.50)*	26.65(0.79)	29.48(0.99)	28.69(0.76)
θ^{CFO}_{body} (°)	28.12(1.08)	30.13(0.55)	28.68(0.85)	30.51(1.07)	29.93(0.82)
$\Delta\theta_{body}$ (°)	2.58(0.54)*	1.12(0.27)*	2.03(0.43)	1.02(0.54)	1.24(0.41)
θ^{FC}_{foot} (°)	-1.80(3.77)	1.30(1.90)	-0.93(2.97)	2.31(3.73)	0.64(2.87)
θ^{CFO}_{foot} (°)	16.00(3.24)	10.95(1.64)	14.16(2.56)	13.07(3.21)	9.40(2.47)
$\Delta\theta_{foot}$ (°)	17.80(2.71)*	9.65(1.37)*	15.09(2.14)	10.76(2.69)	8.76(2.07)
d^{FC}_{NORM}	0.20(0.03)	0.25(0.02)	0.23(0.03)	0.26(0.03)	0.23(0.03)
d^{CFO}_{NORM}	0.18(0.03)	0.23(0.01)	0.20(0.02)	0.24(0.03)	0.23(0.02)
Δd_{NORM}	-0.01(0.02)	-0.02(0.01)	-0.04(0.02)	-0.02(0.02)	0.00(0.02)
VF	0.84(0.07)	0.81(0.03)	0.85(0.05)	0.82(0.06)	0.78(0.05)
HF	0.39(0.07)	0.40(0.03)	0.45(0.05)	0.36(0.06)	0.38(0.05)
FR	0.46(0.05)	0.49(0.02)	0.52(0.03)	0.44(0.04)	0.49(0.03)

Slip Statistical significant: * $p < 0.05$; Age Group Statistical significant: ^{X} $p < 0.05$
FC = foot contact; CFO = contralateral foot-off; θ^{FC}_{body} = body angle at foot contact; θ^{CFO}_{body} = body angle at contralateral foot-off; $\Delta\theta_{body}$ = change in body angle between foot contact and contralateral foot-off; θ^{FC}_{foot} = foot angle at foot contact; θ^{CFO}_{foot} = foot angle at contralateral foot-off; $\Delta\theta_{foot}$ = change in foot angle between foot contact and contralateral foot-off; d^{FC} = foot placement at foot contact; d^{CFO} = foot placement at contralateral foot-off; Δd = change in foot placement between foot contact and contralateral foot-off; NORM = normalized to foot length; VF = Vertical Force; HF = Horizontal Force; FR = Force Ratio

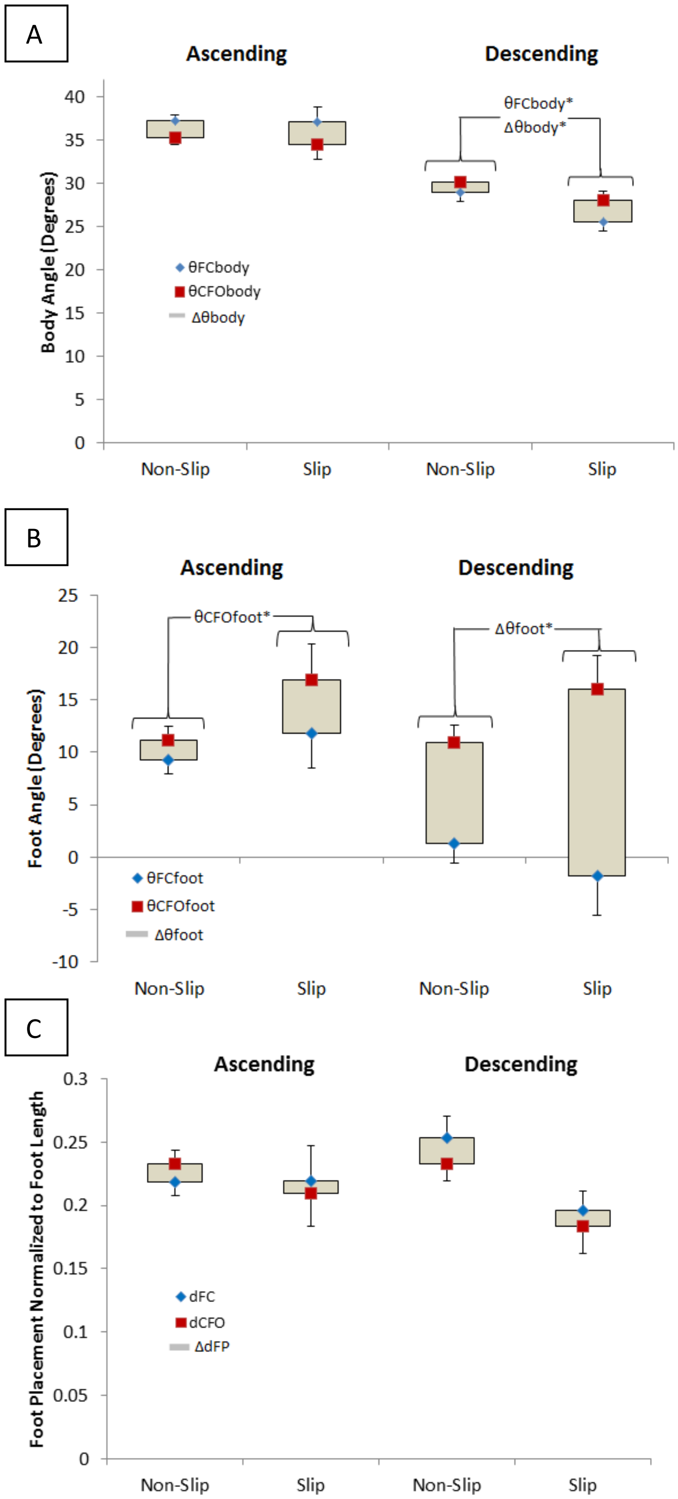


Figure 7: (A) Body angle (B) Foot angle (C) Foot Placment at foot contact (FC) and contralateral foot-off (CFO) and change between FC and CFO: Ascending (left) Descending (right). Foot contact is denoted by the blue triangle. Contralateral foot-off is denoted by the red square. Error bars off the symbol represent the standard deviation of the denoted position. The change in the body/foot parameter is the difference between contralateral foot-off and foot contact. The change is denoted through the gray box.

2.4 Discussion

Restricted toe clearance was found to dramatically affect slip outcomes, while hand positioning and climbing direction did not have a strong effect. This study suggests that fixed ladders which constrain a climber's foot placement will increase the climber's probability of slipping. Age group was also found to influence slip risk with the youngest age group at the highest risk followed by the eldest age group. Participants who slipped climbed with different double support time, foot positioning and body positioning than participants who did not slip indicating that certain climbing styles are safer than others.

Toe clearance restriction, which constrains foot placement, had a strong effect on slip outcome. Foot placement for the unrestricted toe clearance condition ranged from 19.9% to 56.1% of foot length (50.82 mm to 143.08 mm) for ascending and 16.6% to 62.4% of foot length (43.77 mm to 160.86 mm) for descending. Foot placements for the restricted toe clearance conditions ranged from 4.9% to 34.7% of foot length (13.43 mm to 83.28 mm) for ascending and 7.9% to 36.1% of foot length (17.49 mm to 88.30 mm) for descending. Fixed ladders may not always accommodate the range of toe space required to allow for unrestricted climbing. Increased slipping risk was identified in this study when the toe clearance approximated the minimum requirements of MSHA (76 mm). The maximum toe clearance observed in the unrestricted conditions was less than the minimum requirement for OSHA (180 mm). This suggests that the OSHA rule exposes workers to significantly less slip risk than the MSHA rule. Some exemptions to the OSHA rule reduce the required toe clearance to 100-110 mm, which might increase slip risk since it is less than the maximum toe clearance in this study and would therefore restrict the toe clearance in some subjects. The results of this study suggest that individual slip and fall risk could be dramatically reduced in the mining industry by increasing the toe clearance requirement. While the results of this study suggest that the OSHA rule for general industry is sufficient, marine terminal ladders, elevator pit ladders and non-compliant ladders may impede toe space and increase fall risk.

Hand positioning was insignificant to slip outcome. This finding may be because the foot supports most of the load during ladder climbing and low friction was only induced to the feet in this study. Other research suggests that hands may be more relevant to the recovery response after a slip has occurred rather than contributing to slip risk, itself. For example, faster muscle response occur when placing hands on the rung compared with the rail (Paul et al. 2013) and greater break-away strength is achievable when grasping horizontal surfaces rather than vertical surfaces (Young et al. 2009).

Slip risk was significant with age group. The youngest age group (18-24 yrs.) slipped the most (20.0%) followed by the eldest age group (44-64 yrs.) (13.3%). These results partially contradict incident rates reported by for the Bureau of Labor Statistics (BLS) reports. The BLS shows that the highest fall rates occur with adults over 45 y.o., which is inconsistent with our study. Possible reasons for this discrepancy might be underreporting of falling incidents by younger employees in industry or that younger employees compensate for increased slip rates with an improved ability to recover from a slip and therefore do not get injured as frequently. The BLS data shows a slight dip in fall rates between adults 20-24 (incidence rate: 4.9) and adults 25-34 (incidence rate: 4.2), which is consistent with the drop in falls that this study observed between adults aged 18-24 and 25-44. One possible explanation for the observed V-shaped relationship amongst age groups and slip outcome may be that inexperience among the youngest age group increases their slip risk, while age-related changes in strength, body mass, coordination and individual biodynamics increase slip risk for the oldest group. While this study did not specifically examine experience as an independent variable, the younger age group is likely to have less ladder climbing experience on average. This lack of experience may have caused them to climb with a non-optimal technique, causing an increase in slip risk. The increase in slip risk for the older age group is likely explained by a different mechanism. Other studies have also found increased slip risk with older age groups (Webster 2000; Moyer et al. 2006; Moore et al. 2009) due to reduced strength, slower response times (Chambers and Cham 2007) and changes to their gait patterns (Moyer et al. 2006). Body mass increased

with older age groups, which may also have explained their increased slip risk since mass may be a confounding factor. These mechanisms may have caused increased slip risk in this study although additional research is needed to identify the precise mechanisms that are responsible. Since younger and older age groups are at high risk of slipping, specific attention and training may be most beneficial for these two age groups.

Double support time and body and foot positioning were significantly different between slipping and non-slipping climbing styles, while foot forces and climbing speed were not significant. Those who slipped had a longer double support time and greater change in body and foot angle compared to those who did not slip (Figure 6). Another possible explanation for a longer double support time and greater body and foot angle change may be that subjects who slipped had difficulty supporting their weight while stabilizing their foot or body. A larger double support time may indicate that subjects slowed weight acceptance because they had difficulty stabilizing their foot or body. Since the foot is the primary supporting load between the ladder and climber, it is critical that the foot can stabilize to accept the climber's weight. Foot stabilization may be accomplished through the production of ankle plantar flexor moments. The increased changes in body angle may indicate that body movement was not controlled as tightly in climbing styles leading to a slip. Improved ladder climbing training may have potential for improving this control and reducing slip risk.

While more climbing biodynamic measures influenced slipping during descent than during ascent, slip risk was not significantly greater during descent. One factor (foot angle at foot contact) was significant during the ascent, while four factors (double support time, body angle at foot contact, change in body angle and change in foot angle) were significant during descent. This suggests that double support time and body and foot positioning may be more important when descending a ladder than ascending a ladder. Descending a ladder may require more precise movement patterns due to impaired visual feedback because the feet are progressing to a rung that is below the climber and is more obstructed from the

climber's vision. Descending may also require more care since energy is being absorbed instead of generated.

Slip risk was not different between ascent and descent. The same number of slips occurred on ascent as descent. The number of slips during descent may have been slightly affected because descent trials occurring after an ascent slip were removed from the analysis. Therefore, future studies that induce a slip during just descent or ascent may be needed to confirm whether climbing direction induces slip risk. Other studies have found the egress process to have a higher injury rate than the ingress process (Moore et al. 2009). Contradiction between the present study and the study by Moore et al. may also be due to workers in the other study being exposed to vibrations, extended working times and fatiguing work tasks between ascent and descent of the ladder.

The horizontal to vertical foot force ratio proved to be insignificant with regards to slip outcome, which appears to contradict some previous research. Bloswick and Chaffin suggested that climbers were at risk for forward slipping based on the forward foot forces that were observed during climbing (Bloswick and Chaffin 1990). Yet, subject's feet tend to be inclined during climbing indicating that the forward forces observed during climbing may not actually be friction forces but might instead contribute to the normal force on the surface of the shoe. Therefore, it may be necessary to project contact forces onto the foot as opposed to the ladder in order to infer required friction limits as well as the slip direction during climbing. One other potential reason that no forward slips were observed is that the footwear used in this study had a raised heel, which may have restricted forward slipping.

Future research may provide additional insight by considering additional ladder types, additional degrees of toe clearance restriction and more specifically identifying the underlying causes for the age effects. This study only considered a single vertical ladder design. Additional research is needed to determine if the conclusions of this study also apply to extension ladders, step ladders and ladders with

different rung and rail designs. While this study identified that toe clearance restriction was a critical factor, not enough degrees of toe clearance restriction were considered to precisely identify the threshold where restricted toe clearance increases slip risk. Lastly, this study identified that slip risk was highest in the youngest age group (18-24 yrs.) and second highest in the oldest age group (44-64 yrs.). Future research that quantifies which factors that are related to age (experience, strength, reaction time, body mass and climbing style) are most relevant to slipping may provide insight into the underlying causes by which age influences slip risk.

Chapter III

Study 2: Ladder climbing factors that affect the severity of falls from ladders

This chapter was written such that the content could be submitted for publication as a stand-alone manuscript. Therefore, some background material is repeated from earlier chapters. In addition, similar content of this chapter has been published in abstracts for the 39th Annual Meeting of the American Society of Biomechanics, 2015 (Pliner et al. 2015.a; Pliner et al. 2015.b).

3.1 Introduction

Ladder falls are the leading cause of fatal falls (Bureau of Labor Statistics 2012.a) and 63 percent of ladder injuries result in a fracture or sprain (Partridge et al. 1998). Nearly half of these ladder fall fractures account for over $5,000 in medical cost (Smith et al. 2006). However, these severe injuries are believed to be preventable through safer ladder climbing practices and proper ladder climbing training (Muir and Kanwar 1993; Socias et al. 2014). Identifying the climbing practices associated with reduced fall risk and the individuals at risk for falling may be an effective strategy at reducing the number of people who suffer from injuries of ladder falls.

The majority of ladder fall fatalities occur by the climber falling from the ladder or the climber falling with the ladder (Shepherd et al. 2006). A fall <u>from</u> a ladder is the result of the climber losing supporting hand and/or foot contact with the ladder. A fall <u>with</u> ladders is typically a result of unstable ladder placement (Shepherd et al. 2006; Smith et al. 2006; Hsiao et al. 2008). Recommendations to prevent falls with ladders have been made by design improvements and proper ladder setup. Hooks, grooves and straps for the top of the ladder have been developed to improve the upper ladder stability (Hsiao et al. 2006), while previous research has investigated the impact of extension ladder angle and ladder shoe friction on stability of the ladder (Chang et al. 2004; Chang et al. 2005). Previous products and research

studies have focused on preventing tipping/slipping at the top and base of the ladder, but there has been limited research on falls from ladders.

Contradicting evidence exists regarding gender effects on ladder fall severity. Male workers account for the majority of ladder fall injuries (Socias et al. 2014) and incur more severe ladder fall injuries than female workers (Bjornstig and Johnsson 1992). However, females have less upper body strength than males (Miller et al. 1993) and increased upper body strength is believed to be critical to prevent a ladder fall (Hur et al. 2012). Also, females tend to have smaller hands, which may not be ideal for typical ladder rungs. Epidemiology data reveals males to have a greater occurrence of ladder falls with higher severity in injury, but differences in strength and anthropometry suggest that female climbers may be at greater risk to a ladder fall. Thus, controlled laboratory studies may be able to better characterize the effects of gender on ladder falling risk.

An occupational task factor that may affect fall risk is climbing direction (ascent/descent). More injuries occur for miners exiting off of mining equipment than entering (Moore et al. 2009). One explanation that was offered by the authors of these studies 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 (Moore et al. 2009). However, previous research has suggested that exposure to vibration does not have substantial short-term impacts on balance (Santos et al. 2008; Cornelius et al. 1994). An alternate hypothesis is that more falls are experienced during ladder descent because descent is an inherently more dangerous task than ascent. Ladder descent requires more time than ladder ascent (Hammer and Schmalz 1992), which may indicate that descent is more challenging. 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. Although injury records show more descending ladder falls than ascending, no study has tested the effect of climbing direction in a controlled environment to

determine if climbing direction contributes to a person's fall severity from a ladder perturbation independent of occupational factors. In addition, ladder ascent and descent utilize different mechanics to climb.

Another occupational factor that is believed to contribute to fall risk during ladder climbing is the coupling between the hands and the ladder rungs or rails (Barnett and Poczynok 2000). Increasing friction between the rung and hand has been investigated as a means to improve recovery from a ladder fall (Hur et al. 2012; Hur et al. 2014). High friction gloves have been shown to increase the amount of force a person can generate onto a rung before the rung was pulled out of their grasp (Hur et al. 2012), whereas low friction gloves increased the muscular effort required to stabilize an upward moving rung (Hur et al. 2014). Previous research has suggested that the increased force generation from high friction gloves may improve one's ability to stop a ladder fall. Alternatively, gloves may hinder the response to a perturbation by delaying the timing at which the hand starts to develop force on the rung (Hur et al. 2014), which would increase free fall time and fall severity (Barnett and Poczynok 2000). 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 seated position (Hur et al. 2014; Barnett and Poczynok 2000) without consideration of the role that the rest of the body plays during a ladder fall. This method may be an over simplification of the effects gloves have between the hand and rung during an actual ladder falling scenario. Thus, additional research is needed to determine if these changes in grip strength translate into improved ability to recover (reduced fall severity) from a ladder perturbation.

The recovery response that is initiated by the individual in response to a fall perturbation is another factor that likely impacts fall severity from a ladder perturbation yet is not well understood. Climbing style has been demonstrated to vary across individuals (Hammer and Schmalz 1992) and individual climbing style is known to affect slip risk (Pliner et al. 2014). Ladder climbing styles that have been investigated are

two-point (one hand, one foot) and three-point contact (one hand, two feet or two hands, one foot). While few ladder users climb using three-point contact for all time periods on fixed ladders (Vi 2008), ladder climbers who maintain three-points of contact during the critical portion where the body is vulnerable to falling or who reestablish three-points of contact quickly after experiencing a perturbation may have a lower fall risk. Furthermore, different outcomes when attempting to reestablish points of contact seem likely to impact a person's ability to reduce fall severity from a ladder perturbation.

The purpose of this study is to determine personal, occupational and recovery responses that are associated with fall severity from ladder slip events. To analyze these factors, this study will consist of two analyses. The first analysis will consider the impacts of gender, climbing direction and wearing gloves on fall severity. H1.1: Female ladder climbers will have a more severe fall following a perturbation than their male counterparts. H1.2 Falls during ladder descent will result in a more severe fall outcome compared to ladder ascent. H1.3: Falls with high friction gloves will result in a less severe fall outcome compared to bare hand and low friction glove conditions. The second analysis will consider the impacts of the upper and lower body recovery response on the outcome of the perturbation. H2.1: Different hand placements following the perturbation will affect fall severity. H2.2: Different foot placements following the perturbation will affect fall severity.

3.2 Materials & Methods

3.2.1 *Subjects*

Thirty-five participants between the ages of 18 and 29 years were recruited. The demographic consisted of 22 males (24.2 ± 5.0 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, neurological disorders, balance disorders and pregnancy. This study was approved by the University of Wisconsin-Milwaukee Institutional Review Board (Protocol Number: 11.366).

3.2.2 Experimental *Approach*

Testing sessions started by recording the mass and height of each participant. Participants were 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 accidentally 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 E). 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). A vertical 12-foot custom-designed ladder was secured in the middle of the motion capture volume (Figure 8). The ladder had twelve cylindrical rungs spaced 304.8 mm (12 in) apart, in compliance with OSHA standards (United States Occupational Safety Health Administration 2003). All rungs excluding rung four 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 of each rung, positioned in the center. A simulated misstep perturbation was induced on the fourth rung by releasing the rung under the foot during climbing. The left and right side of the rung had a spring-loaded connector inside the rung. A rod was used to compress each spring-loaded connection to attach the rung with the ladder. The rod and spring connection was held in place with electric magnets during baseline climbing. When the rung was triggered to release, the magnets would demagnetize and the springs would extend, breaking the rungs connection with the ladder. The rung was programed to release when less than five percent of the participant's body weight remained on the previous rung. The timing of this contralateral foot-off

corresponds to climber's most likely time of slip (Paul et al. 2013). To ensure participant safety, each participant had an impact mat at the bottom of the ladder, a spotter and belayer.

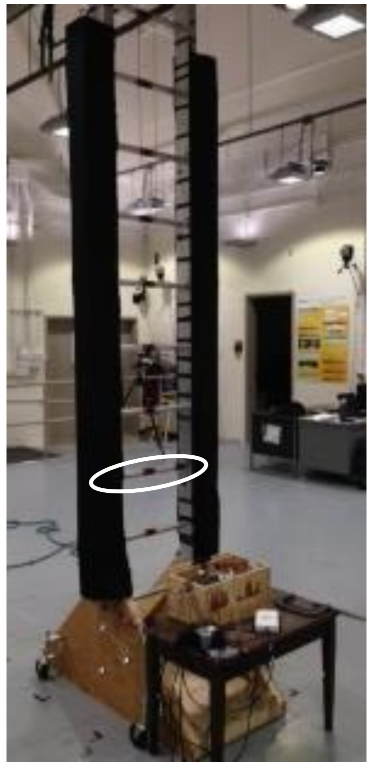


Figure 8: Study 2 custom-designed ladder. The ellipse encircles the releasing rung.

Participants were perturbed six times while ascending and descending the ladder out of 30 total ascents and descents. The perturbations were conducted for both climbing directions (ascent and descent) and across three different glove conditions (bare hands, high friction and low friction). 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 climbs were collected prior to each perturbation to reduce anticipation of the perturbation (Pliner et al. 2014). Participants were instructed to climb at a "comfortable but urgent pace" to simulate climbing speed of a regular to busy workday.

3.2.3 ***Data and Statistical Analysis***

3.2.3.1 Analysis 1

Fall severity to a ladder perturbation was measured by the weight supported by the safety harness. Where a high harness force was associated with a more severe fall. The harness force was normalized to each participant's body weight and calculated as the peak force between the start of fall and end of fall (Appendix F). Start of fall was the point in time the rung was triggered to release. The end of fall was the point in time of the first minimum of the mid-hip joint center's vertical displacement after start of fall (Pavol and Pai 2002). Mid-hip joint centers were calculated using Bell's Method and the ASIS and PSIS markers (Bell et al. 1990) (Appendix D).

A mixed-measures ANOVA was performed with subject number (random), gender, perturbation number (continuous), climbing direction, glove condition, and the first order of interactions as independent variables. Perturbation number was added to the model to adjust for potential adaptation. Harness force was normally distributed with a square root transformation and set as the dependent variable. Hypothesis 1.1 would be confirmed if females had significantly higher harness forces than males. Hypothesis 1.2 would be confirmed if missteps during ladder descent resulted in significantly higher harness forces than ladder ascent. Hypothesis 1.3 would be confirmed if high friction gloves resulted in significantly lower harness forces compared to the bare hand and low friction glove conditions.

3.2.3.2 Analysis 2

Initial review of the upper body responses revealed four different categories of upper body responses based on the movement of the hands after the perturbation. Hand response was analyzed for the hand that was in motion or the hand that would move next (i.e. for ladder ascent, this would be the lower hand). The hand was in motion if the hand did not have contact with the rung at the start of fall. The next hand to move was a hand that had hand contact at the start of fall, but did not have hand contact for the full falling time period or was not in contact with a rung throughout the falling time period. Four

hand movements (HM) were observed: HM2-Hand continued to next rung as planned (moving two rungs up during ascent or two rungs down during descent from starting position); HM1-Hand interrupted the planned path of motion and grasped one rung before the intended rung (grasping one rung above during ascent or one rung below during descent from starting position); HM0-Hand momentarily elevated from starting position before re-grasping the same rung; HMN-Hand did not move. Trials where the other hand released the rung and grasped a lower rung were excluded (n=2/89 for ascent and n=2/79 for descent). If a hand response did not occur more than 5% in a climbing direction, trials where that hand response was utilized were excluded from the statistical analysis.

Initial review of the lower body responses revealed three different categories of foot placements during recovery. The foot response of both feet were analyzed together. Three types of feet movements (FM) were observed: FM2-Two feet hit the top of the rung(s) and reestablished foot placement on the rung(s); FM1-One foot hit the top of the rung and reestablished foot placement on the rung (both feet may have hit rung(s), but only one reestablished foot placement on a rung); FM0-The feet did not hit the top of the rungs or the foot/feet hit the top of the rung(s), but did not reestablished foot placement.

Hand and feet responses were verified by hand and foot contact times at the start of fall and at the end of fall. Hand and foot contact times were determined from the vertical strain gauge data of the ladder rungs. The data was processed through a notch filter to remove electrical noise before data analysis. Rung contact time was determined from the point in time strain activity exceed or fell below a calculated strain limit. The rung contact time was calculated based on the first time point that the strain exceeded 10% of the peak strain activity. For the perturbed trial (which had a higher peak strain due to the recovery response), the strain threshold for contact time was set to 10% of the peak strain activity averaged across the baseline trials. In addition, contact time was visually checked and confirmed with motion data.

An ANOVA was performed with subject number (random), hand response and feet response as independent variables and the square root normalized harness force as the dependent variable (Hypothesis 2). ANOVAs were run separately by climbing direction because mechanics to ascend and descend a ladder differ. Gender, perturbation number and glove condition that are found to be significant in Analysis 1 were included as covariates in this analysis. Hypothesis 2.1 would be confirmed if harness forces for hand responses were significantly different. Hypothesis 2.2 would be confirmed if reestablishing foot placement back onto the rung resulted in significantly lower harness forces.

3.3 Results

3.3.1 Analysis 1

Hypothesis 1.1 and 1.2 were confirmed, but not hypothesis 1.3. Females had significantly higher harness forces than males ($p = 0.003$, $F = 10.400$). Specifically, normalized harness forces were 0.22 and 0.38 for males and females, respectively. Descending perturbations were nearly 50% higher than ascending perturbations ($p < 0.001$, $F = 23.570$). The average harness force for bare hands, high friction and low friction gloves were 0.25 (0.21), 0.30 (0.28), and 0.32 (0.27), respectively. Glove condition did not significantly affect harness force ($p = 0.253$, $F = 1.415$). Harness force did not significantly change across the six perturbations ($p = 0.334$, $F = 10.400$) (Figure 9).

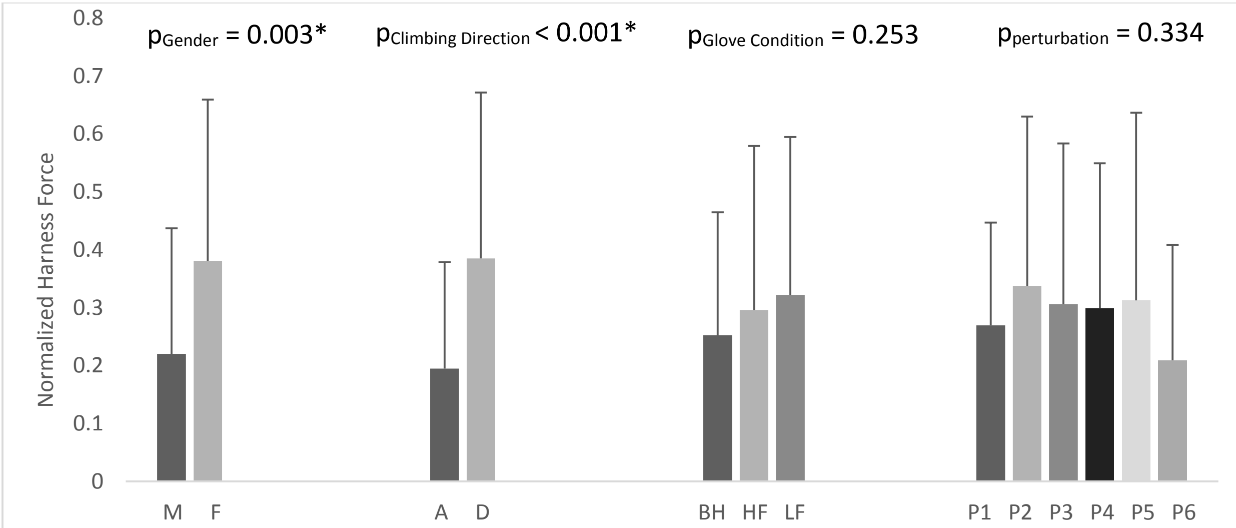


Figure 9: Average harness force normalized to body weight for males (M) vs. females (F), ascend (A) vs. descend (D), bare hand (BH), high friction (HF) vs. low friction (LF), and perturbations one (P1) through six (P6).

3.3.2 Analysis 2

Hypotheses 2.1 and 2.2 were confirmed for perturbations during ascending ladder climbs. The motion path the moving hand or next hand to move made during the fall varied across participants: HM2-the hand grabbed the target rung in 26% of trials; HM1-the hand interrupted the planned path of motion and landed at the next rung in 11% of trials; HM0-the hand left the rung and came back down onto the same rung in 24% of trials; HMN-the hand did not move in 38% of trials. (Table 4). Participants who interrupted the hand's planned path of motion, landing only one rung above the starting position (HM1) had significantly higher harness forces than the other three hand responses ($p = 0.017$, $F = 3.669$) (Figure 10). The feet response varied during recovery: FM2-both feet reestablished foot placement on top of the rung(s) in 22% of trials; FM1-only one foot reestablished foot placement on top of a rung in 46% of trials; FM0- the feet did not hit the top of the rungs or the feet did not reestablish foot placement on the top of the rung in 32% of trials. Participants who reestablished two feet on top of the ladder rung had significantly lower harness forces followed by people who reestablished one foot on top of the ladder rung compared to those who did not reestablish foot placement ($p < 0.001$, $F = 12.689$) (Figure 11). Gender

was confirmed to be a significant covariate with females accounting for greater harness forces (p = 0.001, F = 7.337).

Table 4: Percentages of hand and foot responses utilized after a ladder perturbation.

Response	HM2	HM1	HM0	HMN	FM2	FM1	FM0
Ascend	26%	11%	24%	38%	22%	46%	32%
Descend	66%	18%	3%	13%	13%	51%	37%

Hypothesis 2.1 was confirmed, but Hypothesis 2.2 was not confirmed for perturbations during descending ladder climbs. Subjects primarily used three of the four hand responses during descent: HM2-the hand grabbed the target rung in 66% of trials; HM1-the hand interrupted the planned path of motion to grasp one rung above the target rung in 18% of trials; HM0-the hand let go of the rung and then reestablished position on the same rung in 3% of trials; HMN-the hand did not let go of the rung in 13% of trials (Table 4). Hand response HM0 was not included in the analysis for descending climbs because the hand response occurred in less than 5% of trials. Participants who did not move their hand during the fall (HMN) had significantly lower harness forces followed by those who interrupted their hands planned path of motion to grab a higher rung (HM1), whereas participants who grasped the target rung (HM2) had the highest harness forces (p = 0.030, F = 3.767) (Figure 10). The feet response varied during descent trials: FM2-both feet reestablished foot placement on top of the rung(s) in 13% of trials; FM1-only one foot reestablished foot placement on top of a rung in 51% of trials; FM0- the feet did not hit the top of the rungs or the feet did not reestablish foot placement on the top of the rung in 37% of trials. Similar to ascent, participants who reestablished both feet on top of the ladder rung had the lowest harness forces, but the difference between feet response was not significant (p = 0.053, F = 3.064) (Figure 11). Again, females were confirmed to have significantly higher harness forces than males (p = 0.008, F = 8.600).

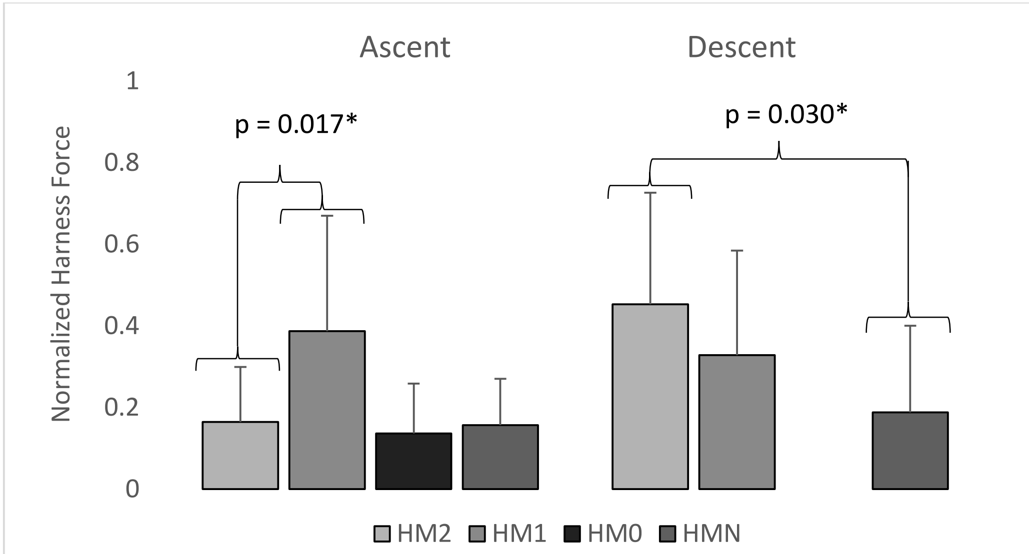


Figure 10: Average harness force normalized to body weight for hand responses during ascent (left) and descent (right) ladder fall recovery.

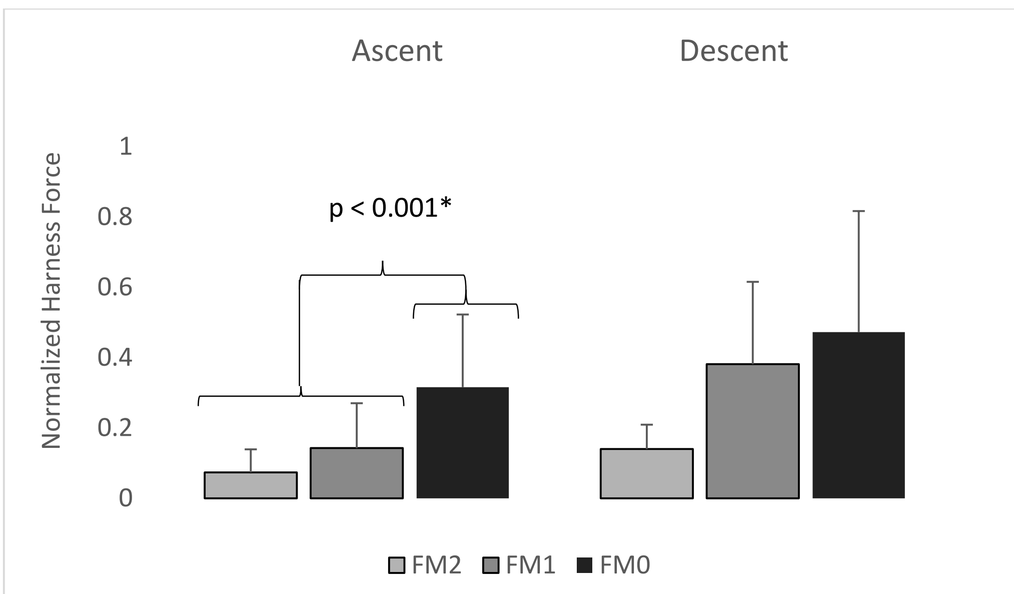


Figure 11: Average harness force normalized to body weight for feet responses during ascent (left) and descent (right) ladder fall recovery.

3.4 Discussion

Personal, occupational and recovery responses were determined to affect the severity of fall from a ladder. Specifically, gender was an important personal factor with female participants having more

severe falls than male participants. Climbing direction was an occupational factor that influenced fall severity with more severe falls occurring during descent, whereas glove usage was an occupational factor that did not affect ladder fall severity. Both the recovery responses of the hands and feet had an impact on fall severity. Specifically, participants who interrupted their hands plan path of motion had more severe falls during ascent whereas participants who did not move their hand during the fall had less severe falls during descent. Feet responses also affected fall severity during ascending perturbations but not during descent. Participants who were able to reestablish at least one foot on top of the ladder rung after an ascending misstep were found to have less severe falls.

Female participants were found to have more severe falls from ladder perturbations than male participants. This may be due to upper body strength (Muir and Kanwar 1993) or anthropometric differences between males and females. Although there was not enough power in this study to investigate the gender and feet response interaction, females relied less on their lower body to break their fall than males (Table 5). Males reestablished foot placement on 71% of ascending trials and 65% of descending trials, whereas females reestablished foot placement 65% of ascending trials and 62% of descending trials. Also, female participants were more likely to not move their hand (HMN) during ascending perturbations. Height of the ladder climber is another factor that may explain gender differences in ladder fall severity. Male subjects were taller than females on average ($p < 0.001$) which may have allowed male participants to reach higher for rungs or extend lower to place feet on rungs. Previous research found greater grip strength to be associated with greater forearm and hand size (Nicolay and Walker 2005). In addition, females have smaller optimal grip spans than males and the ladder rung sizes used in this study may have been more similar to the male subjects' optimal grip spans (Fransson and Winkel 1991). Ladder design is based off the climbing biomechanics which was originally performed using male populations (Chaffin and Strobbe 1979). Thus, females may have difficulty recovering from a fall because the size of the ladder may not be optimal for their body to reach and grasp ladder rungs or extend their lower body to ladder rungs.

Interestingly, children accounted for 50% of fixed ladder fall injuries within two hospitals, which may further support that incongruence between design and anthropometry increases fall risk (Bjornstig and Johnsson 1992). Ladder falls may be reduced if ladder design is based off a specific climber size in order to enable all participants to utilize the most beneficial hand and foot responses. Another gender difference between males and females is weight ($p < 0.001$). Employees with BMI levels greater than 26 experience more falls those with BMIs under 26 (Chau 2004). Thus, greater weight in males than females may contribute to increasing fall severity, but other gender affects such as strength, height, arm length and hand size may overcome the effects of weight.

Table 5: Percentages of hand and foot responses utilized after a ladder perturbation by gender and climbing direction.

Response		HM2	HM1	HM0	HMN	FM2	FM1	FM0
Ascent	Males	30%	7%	33%	30%	29%	42%	29%
	Females	21%	24%	15%	41%	13%	52%	35%
Descent	Males	61%	16%	2%	20%	16%	49%	36%
	Females	63%	17%	3%	17%	9%	53%	38%

Previous researchers have attributed the higher fall rates observed during descent relative to ascent from job tasks that occur between ascent and descent such as exposure to vibration or fatigue (Cornelius et al. 1994). However, this study suggests ladder descent is inherently a more hazardous task than ladder ascent. Climbers' momentum during ladder descent may increase the difficulty to stop a ladder fall. Participants ascending the ladder have more time to respond to the misstep due to the delay between when they lose their foot support and when their center of mass begins moving downwards. During descent, participants' center of mass is already moving downward and they may have to respond faster to stop a fall. One solution to preventing ladder falls during descent may be utilizing additional climber to ladder devices during descent such as a metal rail and safety locking sleeve (Vi 2008).

Fall severity during ascending ladder falls can be decreased by hand and feet responses. Falls during ladder descent can be improved through utilizing optimal hand responses. Lower harness forces

associated with grasping a higher rung during ascent and with maintaining grip on a higher rung during descent may be explained from the increased strength associated with an extended arm posture (Salehi et al. 2014). To increase probability of the hand grasping the higher rung during an ascending ladder misstep, one should lead with the hand before the foot. Also, the foot hitting the top of the ladder rung reduced fall severity from a ladder perturbation. Ladder climbing biomechanics may be modified to encourage foot placement on the rung after a perturbation. Although fall severity was decreased when both feet reestablished foot placement with the rung (FM2), this was not significant during descending ladder perturbations. In addition, the majority of the feet responses during descending perturbations occurred with only one foot reestablishing foot placement (FM1) (Table 4). This uneven distribution of feet responses may have limited the power in this analysis. Many studies have focused on improving ladder fall recovery through ladder and upper body interactions (Barnett and Poczynok 2000; Hur et al. 2012; Hur et al. 2014) but the lower body's interaction with the ladder also has a substantial impact on ladder fall severity.

Glove condition did not affect fall severity. Although previous research believed increased force from high friction gloves would reduce ladder fall severity (Hur et al. 2013; Hur et al. 2014), this study did not find a decrease in fall severity with high friction gloves. One explanation for this effect may be the increased force from high friction gloves improved the response, but was counteracted by an increased in time for the climber to respond to the fall. Another explanation may be that the amount of upper body force required to decelerate the climber's body can be obtained without gloves or that "breakaway" strength is not the limiting factor influencing fall risk. Overall, this study suggests that increased force from high friction gloves does not translate to reducing fall severity in a ladder falling scenario.

Future research may aim to determine if the results of the study are generalizable to workplace ladder falls and across different ladder designs. Ladders are often used in relatively uncontrolled environments

that may include performing multiple tasks, wearing bulky or heavy clothing, and being exposed to different environmental conditions (weather, noise, etc.). Thus, future research may investigate real world falls to determine if the recovery strategies found in the present study also impact fall risk outside of the lab. Many other ladder designs are used in industry besides fixed ladders such as extension and step ladders (Shepherd et al. 2006). The outcomes of this study may only accurately reflect falls from vertically fixed ladders. In addition, the height of this ladder was 12 feet. Although, falls from even low heights can result in severe injures (Muir and Kanwar 1993), over half of falls from heights occur between 11 and 30 feet (Webster 2000). Climbing strategies and recovery responses may change at higher ladder heights.

Chapter IV

Conclusion

Restricted foot placement, age, climbing biomechanics, gender, climbing direction, and recovery responses are factors that affect slip and fall risk. This chapter develops a recommendation and proposed future research based on the results of Studies 1 and 2 for each of these factors.

1. Restricted toe clearance increased slip risk by about 6 times compared to unrestricted toe clearance.

    Recommendation: Ladders should be installed to ensure that the worker's toe clearance is not restricted during ascending and descending climbs.

    Additional Research: Future research should attempt to determine the minimum toe clearance that does not increase slip risk.

2. Younger ladder climbers had less climbing experience and are at greater slip risk.

    Recommendation: Younger workers should have additional training and attention for ladder climbing tasks.

    Additional Research: Studies should investigate ladder slip risk after multiple ladder climbing practice sessions.

3. Greater climbing variation in the individual's body positioning and foot positioning increased slip risk (Figure 7).

    Recommendation: Ladder climbing training should focus on reducing body and foot variation while climbing.

    Additional Research: The effectiveness of training workers to minimize this climbing variability on slip risk should be investigated.

4. Females have a higher fall risk than males.

Recommendation: Ladder design components should be reconsidered with a goal of reducing fall risk of female climbers.

Additional Research: Future studies should determine optimal ladder rung size and spacing across genders to determine if different ladders are needed for female workers.

5. Descending a ladder is a more hazardous task than ascending a ladder.

   Recommendation: Interventions should focus on fall protection during ladder descent. Snap hooks or a safety locking clip with rail may be methods to reduce fall severity (Vi 2008) to make ladder descent safer.

   Additional Research: Elements that may contribute to making descending a ladder a more hazardous task, such as impaired vision, should be investigated.

6. Hand and feet responses after a ladder fall affect fall severity.

   Recommendations: Climbers should try to maintain hand grip with the rungs throughout the fall or grip the ladder rungs with an extended arm to reduce the magnitude of their fall (Figure 10). In addition, climbers should also try and reestablish foot placement after a ladder fall to reduce the magnitude of their fall (Figure 11).

   Additional Research: Future work should investigate climbing mechanics that may cause subjects to utilize a preferred hand and foot response and to determine if these responses are modifiable.

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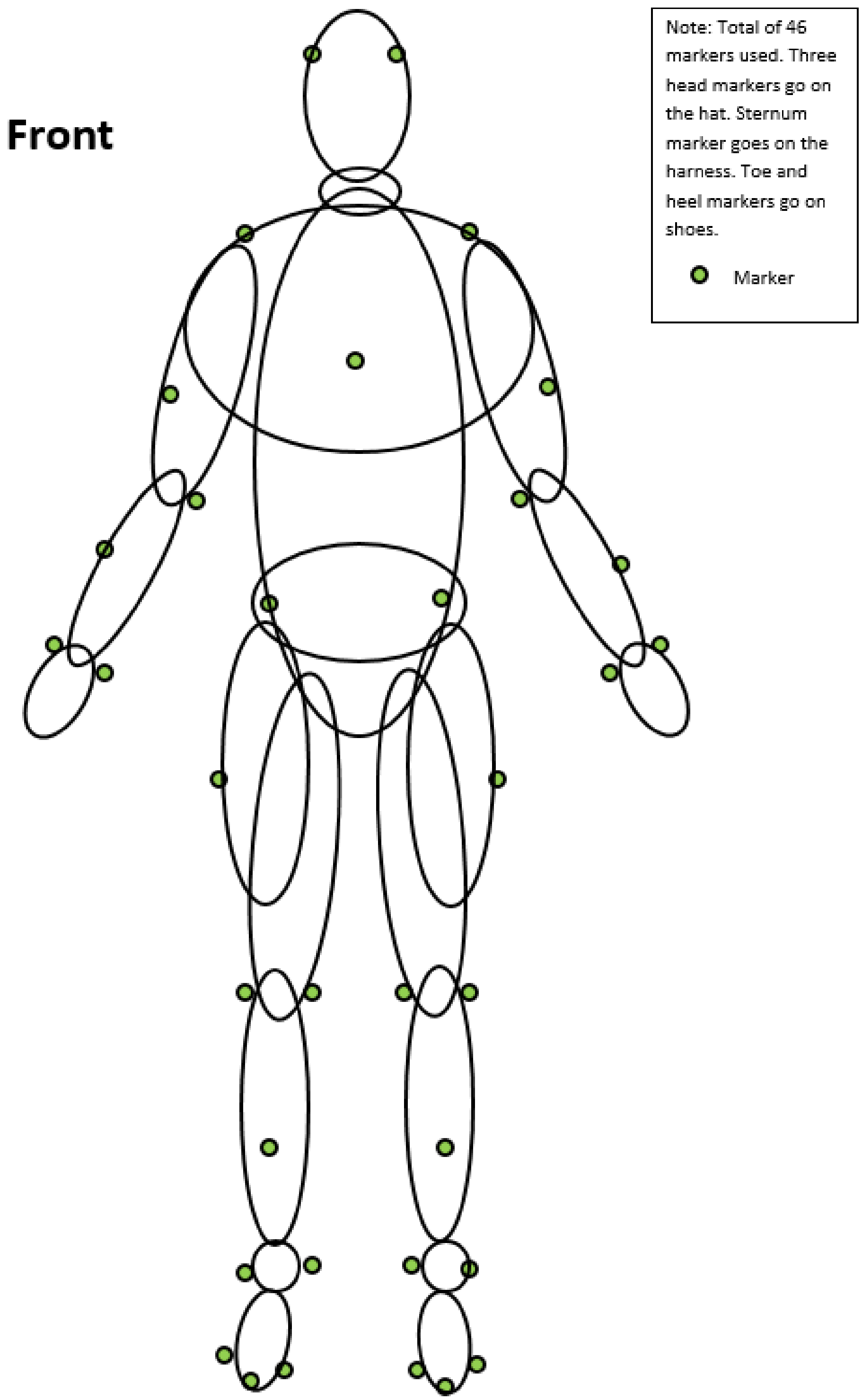
APPENDIX B: Reflective marker placement diagram for study 1



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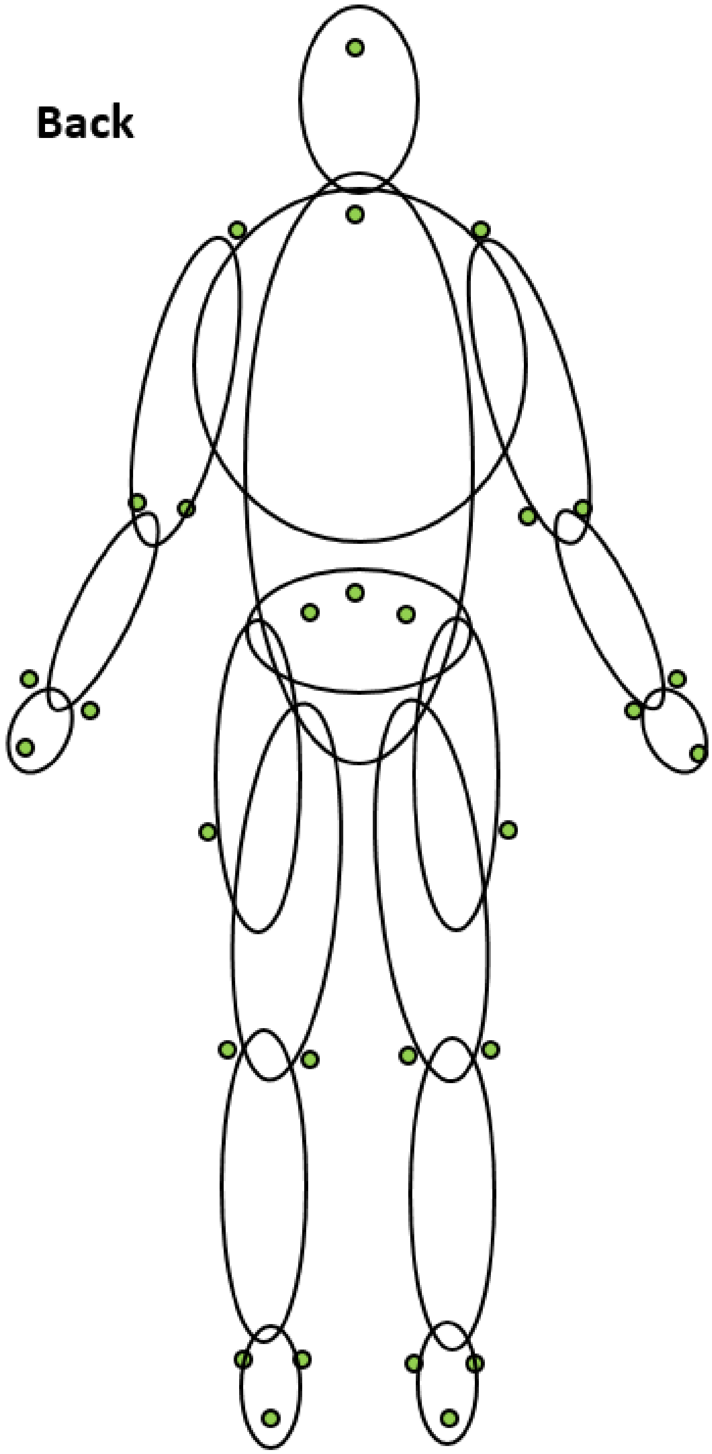
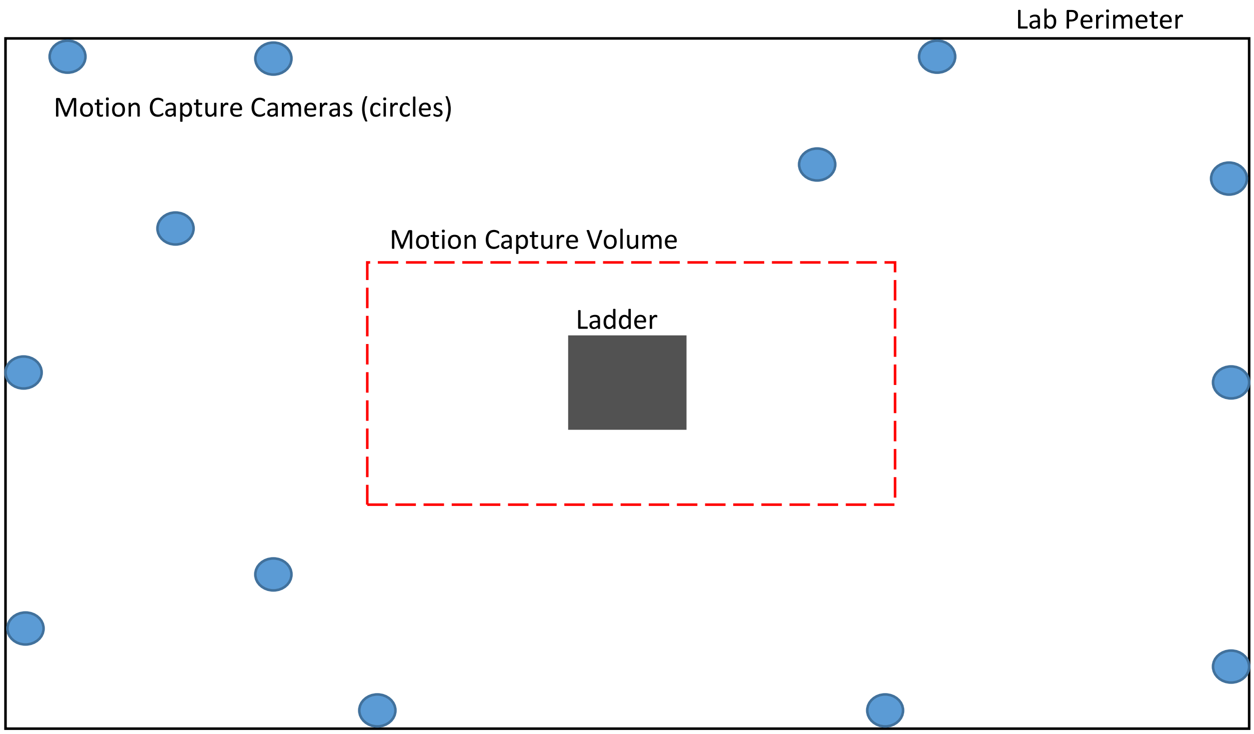


APPENDIX C: Motion cameras, motion area volume and ladder setup layout for studies 1 and 2



APPENDIX D: Bell's Method to calculate the mid-hip joint center

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 ($LHJC_{Pelvis}$).

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

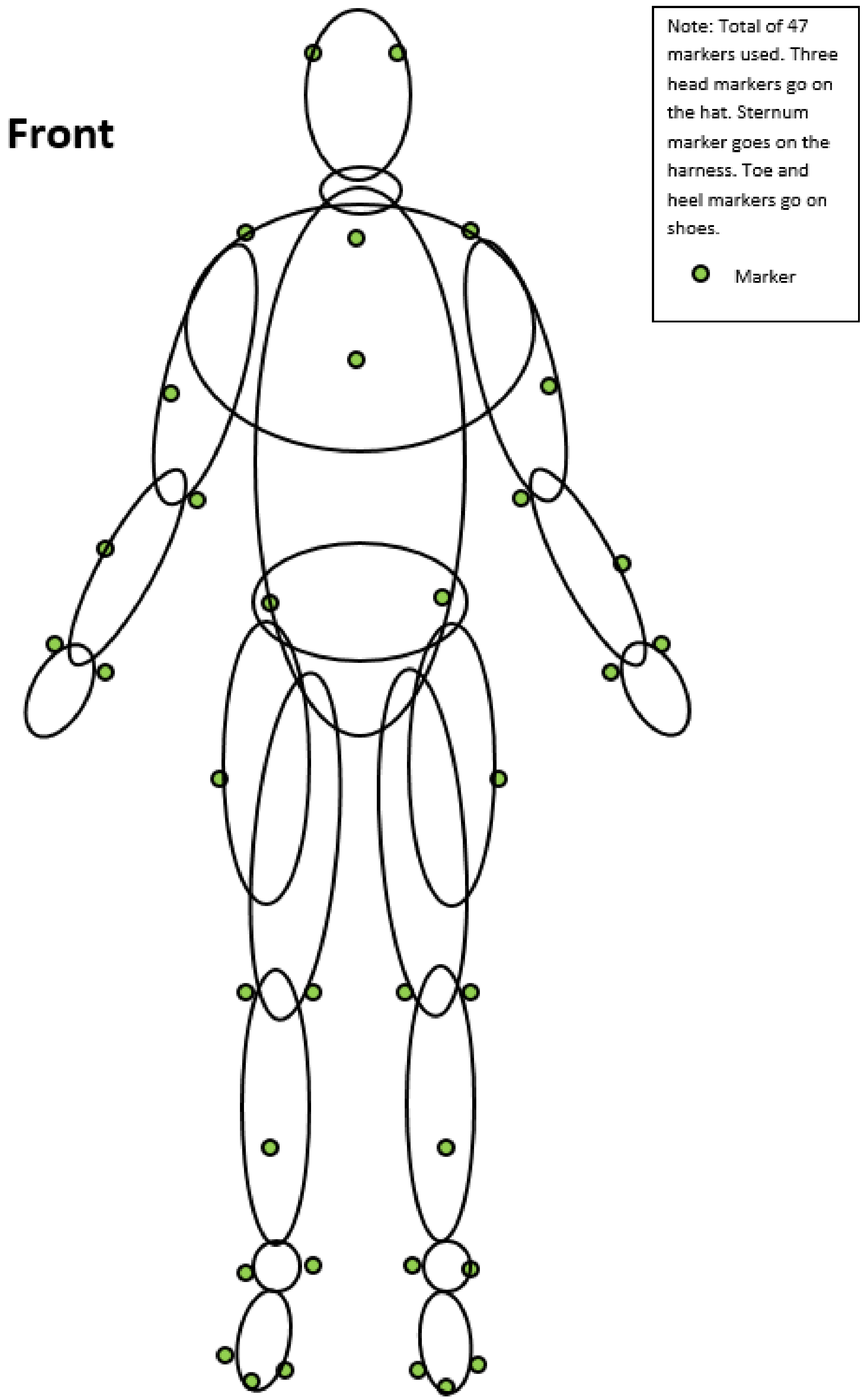
$$LHJC_{Pelvis} = [-0.19 * PW;\ -0.30 * PW; -0.36 * PW]$$

Calculate the location of the Mid-Hip Joint Center (MHJC).

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

**Note the RHJC and LHJC are calculated in the pelvic coordinate system and then transformed into the global coordinate system to calculate the MHJC.

APPENDIX E: Reflective marker placement diagram for study 2



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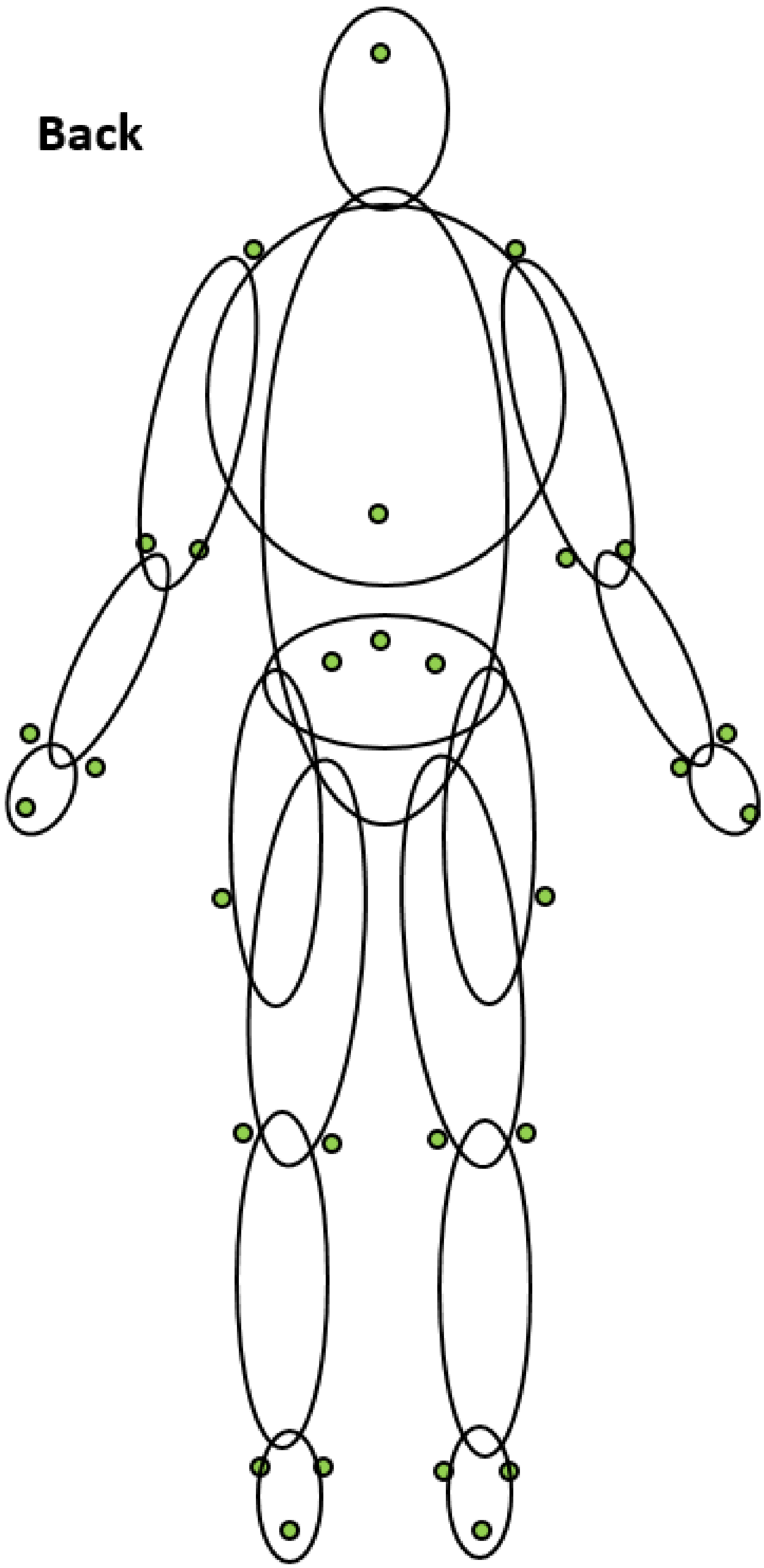

APPENDIX F: Normalized harness force calculation

$$Normalized\ Harness\ Force = \frac{Peak\ Harness\ after\ perturbation}{Climber's Body\ Weight}$$