FINAL PROGRESS REPORT

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Project Information:

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B.List of Terms and Abbreviations

θ^{FC}_{body}: Body angle relative to vertical at the time of foot contact
θ^{CFO}_{body}: Body angle relative to vertical at the time that the foot contralateral to the slip moves off of the rung
$\Delta\theta_{body}$: Change in body angle between the time of foot contact and the time that the foot contralateral to the slip moves off of the rung
θ^{FC}_{foot}: Foot angle relative to horizontal at the time of foot contact
θ^{CFO}_{foot}: Foot angle relative to horizontal at the time that the foot contralateral to the slip moves off of the rung
$\Delta\theta_{foot}$: Change in body angle between the time of foot contact and the time that the foot contralateral to the slip moves off of the rung
d^{FC}: Anterior-posterior position of the toe relative to the rung at foot contact.
d^{CFO}: Anterior-posterior position of the toe relative to the rung at the time that the foot contralateral to the slip moves off of the rung
Δd: Change in foot placement between the time of foot contact and the time that the foot contralateral to the slip moves off of the rung
A: Ascent
ANOVA: Analysis of variance
ASIS: Anterior superior iliac spine
BH: Bare hand
^{CFO}: Superscript denoting the time that the foot contralateral to the slip moves off of the rung
D: Descent
EMG: Electromyography
^{FC}: Superscript denoting the time that the slipping foot contacts the ladder.
F: Female
FP0: Foot placement response after a simulated misstep where none of the feet reestablished contact on a rung
FP1: Foot placement response after a simulated misstep where one of the feet reestablished contact on a rung.
FP2: Foot placement response after a simulated misstep where both feet reestablished contact on a rung.
FR: Force ratio between peak horizontal and peak vertical force
H: Hypothesis
HF: Horizontal force
HiF: High friction
HP0: Hand placement response after a simulated misstep where subjects released a rung and then grasped the same rung (i.e., advanced their hand 0 rungs).
HP1: Hand placement response after a simulated misstep where subjects released a rung and then grasped the next rung (i.e., one rung up during ascent or one rung down during descent).
HP2: Hand placement response after a simulated misstep where subjects released a rung and then advanced their hand to the second rung (i.e., two rungs up during ascent or two rungs down during descent).
HPN: Hand placement response where both hands maintained contact with a rung during the entire time period between onset of the simulated misstep and the end of fall.
$_{NORM}$: Subscript denoting that the variable was normalized to foot length
LF: Low friction
M: Male
OSHA: Occupational Safety and Health Administration
MSHA: Mining Safety and Health Administration
P1: Perturbation 1
P2: Perturbation 2
P3: Perturbation 3
P4: Perturbation 4

P5: Perturbation 5
P6: Perturbation 6
PSIS: Posterior superior iliac spine
SD: Standard deviation
VF: Vertical force

C.Abstract

Falls from ladders represent one of the leading causes of occupational injuries and fatalities. The primary factors contributing to falls from ladders are missteps and foot slips. A critical need exists to identify risk factors and characterize the response to ladder slips and missteps. Over the past three years, we have generated new knowledge on the biomechanical response to ladder perturbations and risk factors that influence the outcomes of ladder falls. These studies have quantified the response to a ladder missteps and slips (Aim 1) and the role of hand strength in recovery (Aim 2). In addition to these aims, we have also identified several risk factors for slipping and falling during ladder climbing.

Aim 1: Slipping and misstep perturbations were analyzed to characterize the response of the contact points (two hands and two feet) after a slip or a simulated misstep. Ten out of fifteen subjects who experienced a slip had only one point of contact with the ladder after the foot slipped off. The events after a ladder slip were sequenced. The hand in motion was the first to re-contact the ladder after the slip followed by the foot contralateral to the slipping foot. The slipping foot was the last to reestablish contact with the ladder. During our simulated misstep experiments, we found four different hand responses and three different foot responses to the perturbation. The hand responses were characterized based on the placement of the hand after the perturbation and included advancing the hands two rungs (e.g., hand movements were the same as unperturbed climbing), advancing the hands one rung (interrupting hand movements to grasp an intermediate rung), re-grasping the rung that the hand was originally grasping, and maintaining both hands on the rung throughout the entire perturbation. The three foot responses were characterized by the number of feet that were placed on the rung after the simulated misstep.

Aim 2: We quantified the effects of glove use and arm posture on maximum pull strength and quantified the relationship between pull strength on recovery during simulated missteps. Increased hand-rung friction and a more extended arm posture were associated with greater pull strength. Certain measurements of hand strength were associated with improved recovery during ascent but not during descent. Differences in pull strength across the three glove conditions did not lead to changes in the recovery. Strength was not found to be as strong of a predictor of recovery as other variables such as hand and foot placement.

Identified Risk Factors for Ladder Climbing: Several risk factors were identified that influenced slip risk and recovery. Restricted foot placement; longer double stance time; more variable foot and body angles; grasping the rungs versus the rails; and being under the age of 25 years were associated with higher slipping risk. Female subjects had more severe falls than male subjects. Less severe falls were associated with ascending the ladder (compared with descending), reestablishing the feet on the rungs and placing the hand on higher rungs.

Section 1 of the Final Progress Report

D.Significant (Key) Findings:

This study led to two key findings related to Aim 1, two key findings related to Aim 2 and three other key findings.

Aim 1: Characterize the sensorimotor response to ladder misstep and slip.

Key Finding 1: We have sequenced the events and muscle activities following an unexpected slip [1]. Our research sequenced the events from foot contact preceding a slip to reestablishing both hands and feet back on the ladder following the slip. This analysis revealed that slipping typically occurs after one hand and one foot had lost contact with the ladder and the only points of contact was the slipping foot and a hand. Thus, slipping typically occurs when people are at their most vulnerable portion of the climbing cycle. We also determined the sequence in which the hands and the feet were reestablished back on the ladder. The hand that was in motion at the time of the slip was placed back on the ladder first followed by the foot contralateral to the slip and then the foot ipsilateral to the slip. Electromyography (EMG) analyses revealed that the triceps activate prior to the biceps and deltoids indicating that elbow extension preceded elbow and shoulder flexion. This finding suggests that the body initially reaches for the rung or extends their arm prior to flexing their elbow and generating forces on the rung. Furthermore, leg muscles activated at approximately the same time as the arm muscles indicating a coordinated response of the upper and lower body.

Key Finding 2: Four different hand placement responses and three different foot placement responses occurred after a simulated misstep. Four different hand placements were observed after the simulated misstep perturbations: 1. both hands maintained grip on the rungs (HPN); 2. one hand released a rung and then re-grasped the same rung (HP0); 3. one hand released a rung and then grasped the next rung (i.e., one rung up during ascent or one rung down during descent, HP1); one hand released a rung and then progressed their hand two rungs (two rungs up during ascent and two rungs down during descent, HP2). During ascent, HPN occurred after 44% of the perturbations, HP0 occurred after 14% of the perturbations, HP1 occurred after 10% of the perturbations, and HP2 occurred after 31% of the perturbations. During descent, HPN occurred after 3.5% of the perturbations, HP0 occurred after 11% of the perturbations, HP1 occurred after 18% of the perturbations and HP2 occurred after 68% of the perturbations. Three different foot placements were observed after the perturbation: placing no feet on the rungs (FP0), placing a single foot on a rung (FP1) and placing both feet on a rung (FP2). During ascent, FP0 occurred in 34% of perturbations, FP1 occurred after 46% of perturbations and FP2 occurred after 20% of trials. During descent, FP0 occurred after 33% of perturbations, FP1 occurred after 69% of perturbations and FP2 occurred after 21% of perturbations.

Aim 2: Determine the contribution of hand strength on fall recovery.

Key Finding 3: Certain hand strength measures were predictive of recovery during ascent but not during descent. Hand strength was measured for five different methods (break-away, pull strength at three different postures and using a handheld dynamometer) and using three different glove conditions. Individual hand strength as measured using two of the postures of pull strength and the handheld dynamometer predicted recovery as measured by peak harness forces during ascent but not during descent. Glove friction was found to alter the break-away strength (increased friction was associated with increased break-away strength) but did not affect harness forces. Therefore, the original hypothesis that hand strength is predictive of recovery is partially supported.

Key Finding 4: Hand and foot placement after perturbation onset is predictive of recovery. During ascent, perturbations where HP1 was utilized had higher harness forces than the HPN, HP0 and HP2. During descent, perturbations where HP2 was utilized had higher harness forces than HP0 and HP1. The hand placements that were associated with increased harness forces (HP1 during ascent and HP2 during descent) also had the longest hand motion times, indicating that longer hand movement time is associated with increased fall risk. Placing one or both of the feet on the ladder after the perturbation was associated with better recovery during ascent but did not have an effect during descent. This study suggests that reestablishing the hands back on the ladder quickly and successfully placing at least one foot back on a ladder rung is more important than an individual’s strength.

Other Important Findings:

Key Finding 5: Restricted foot placement dramatically increases slipping risk [2]. Subjects were exposed to a low friction rung while being randomly assigned to either restricted (toe clearance was limited to 25% of their foot length) or unrestricted foot clearances. Slip risk was 5.5 times more frequent during the restricted foot clearance condition. The restricted foot clearance condition approximated the minimum requirements for ladders as specified by MSHA, whereas the unrestricted condition approximated the minimum requirements for ladders as specified by OSHA. Thus, this finding indicates that ladders that only meet the minimum requirements of MSHA standards likely increase worker slip risk relative to those that only meet the minimum requirements of OSHA standards.

Key Finding 6: Grasping the ladder rungs improves the speed of muscle response after slipping [2]. EMG activity during the slipping trials were analyzed to quantify differences in response time when grasping the rungs versus grasping the rails. Grasping the rails reduced the onset times by 280 ms and the time to peak activity by 298 ms relative to grasping the rungs. Previous research on falls has indicated that slower response times are associated with a worse ability to recover from the perturbation and avoid a fall [3]. Thus, this result suggests that grasping the rails increases fall risk after experiencing a ladder slip.

Key Finding 7: Age and gender influence slip risk and fall risk, respectively. Adults aged 18-24 years and adults aged 45-65 years were found to have an increased slipping risk compared with adults aged 25-44 years [2]. The increased risk among the youngest group was attributed to less experience while the increased risk due to older adults was due to aging effects. Male subjects recovered from a ladder simulated misstep better than female subjects. This gender effect disappeared when accounting for hand and foot placements. Interestingly, women were more likely to utilize the undesired hand (HP1 during ascent, HP2 during descent) and foot placements (FP0). Thus, the increased use of preferable hand and foot placements after a perturbation by male subjects may explain the gender effect.

Translation of Findings:

Training Materials: The results of this study have been translated to occupational safety practices through training materials developed for power plant workers. Specifically, the finding that restricted foot placement increases slip risk (Key Finding 5), that fall risk is higher during descent and that young adults are at greater risk of falling (Key Finding 7) were incorporated into these training materials, which were then presented at train-the-trainer sessions.

Other Potential Translation: Other recently published and soon-to-be published research findings also have potential for immediate translation to the workplace. For example, the reduced response time that was associated with grasping the rungs can be utilized to train workers to grasp the rungs instead of the rails. Also the finding that falls are more severe to ladder descent suggest that additional protections (such as fall protection) should be utilized during ladder descent. We plan to continue disseminating our research results to a broader audience once these findings are vetted and approved through the peer-review process.

Outcomes/ Impact:

Potential Outcomes:

- The finding that restricted foot clearance has the potential to lead to changes in MSHA guidelines. Our results found that the minimum toe clearance required by MSHA is likely to increase slip risk by about 5 times relative to the minimum toe clearance required by OSHA.
- The finding that grasping the rungs improves recovery relative to grasping the rails has the potential to inform best practices in ladder climbing techniques.
- The finding that falls are more prevalent during descent may lead to outcomes to provide additional protection for workers during ladder descent.

Intermediate Outcomes

- The findings related to toe clearance and age have been integrated into safety training programs that are currently being disseminated. A train-the-trainer paradigm is being utilized for this dissemination to achieve broad impact.

End Outcomes

- No end outcomes are noted at this time. Future research is required to determine the effectiveness of the intermediate outcomes on end outcomes.

Section 2 of the Final Progress Report: Scientific Report.

E. Background

E.1. Problem Statement and Significance

Falls to a lower level account for 6% of all non-fatal injuries and 11% of fatalities in the workplace [4, 5]. Ladder-related falls are the leading cause of disabling falls to lower levels [6] and the second-leading cause of fatal falls to lower levels [7]. The median time away from work for disabling falls from ladders is 15 days [6]. Occupational falls to a lower level costs $6.2 billion annually [8], which has increased 34% over the past decade [9]. Ladder-related falls are particularly prevalent in the construction [7] and mining industries [10].

E.2. Previous Studies on Ladder Fall Risk Factors

Previous studies on ladder-related falls have primarily focused on falls *with* a ladder [11-14], although falls *from* a ladder account for a comparable number of fall-related fatalities [15] and a plurality of non-fatal occupational injuries [16]. Falls from a ladder are often caused by decoupling between a worker and the ladder such as hand-ladder decoupling and foot-ladder decoupling [15-17]. Barnett and Poczynok described a three-phase ladder fall scenario: (1) freefall; (2) the time it takes for the person's muscle forces to respond; and (3) deceleration to a stop [18]. While this work provided a framework on the process of a fall from a ladder, it was purely theoretical and was not based on biomechanical analysis of actual falling. Despite the frequency of falls from a ladder, the biomechanical responses that detect and arrest the fall are unknown. This gap in knowledge imposes an obstacle in improving workplaces to prevent ladder-related falls.

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% [19] and 96% [20] of a climber's body weight. Bloswick & Chaffin suggested 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 [21], 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 [22]. 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 [20, 23, 24]. 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 [25], 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. The funded research identified the effects of foot positioning, hand positioning and ascent versus descent on slip and fall 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 [26], 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 [27-31]. In 2008 Maki and colleagues summarized several methodologies aimed at reducing risk of falling related to aging [32]. 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. The completed research identified differences in slipping risk across different age groups.

The completed research expanded current knowledge on biomechanical response to a misstep and slip from a ladder. *This contribution is significant because understanding the biomechanical response to a misstep and slip is needed to redesign workplaces and train workers with desirable climbing methods to maximize the likelihood of a recovery from perturbation during ladder climbing, thereby reducing injuries and fatalities due to falls from ladders.* Specifically, this research will have a *high impact* on the ergonomics community by providing critical information that can lead to targeted interventions for reducing falls from ladders (Fig. 1). Similar to previous studies that identified the physical requirements to climb a ladder [33], this study identified the physical capabilities needed to recover from a fall while climbing. Lastly, we have determined the relationship between hand strength and recovery from a ladder perturbation. This provides necessary context for previous studies that have found that hand strength can be altered by modifying rung size and shape [34], climbing practices such as gripping rungs instead of rails [18, 34], and high-friction glove use [18] . The outcomes of this research are relevant to the National Occupational Research Agenda goals in the National Construction Agenda (Goal 1), National Transportation, Warehousing and Utilities Agenda (Goals 1.14 and 1.27), and National Wholesale and Retail Trade Agenda (Intermediate Goal 2.2).

F.Specific Aims

Aim 1. Characterize the sensorimotor response to misstep and slip during ladder climbing
Aim 2. Determine the contribution of hand strength on fall recovery.

G.Methodology, Results and Discussion

G.1. Scientific Report #1: Effects of foot placement, hand positioning, age and climbing biodynamics on ladder slip outcomes [2]

G.1.1. Methods

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 1). 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 [35]. 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. 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 1: Subject distribution amongst age groups with the mean ± standard deviation of age and body mass 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

G.1.1.1.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 and were tracked by 13 motion capture cameras at a frequency of 100 Hz (Motion Analysis Raptor Corp., Santa Rosa, CA). 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 1). 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 [22]. 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 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 2). 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.

Figure 2: Controlled climbing strategies: (A) Rungs (B) Rails (C) Restricted toe gap (D) Unrestricted foot placement.

G.1.1.2.Analysis

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 [19].

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 ($\theta^{FC}{}_{body}$), body angle at CFO ($\theta^{CFO}{}_{body}$), change in body angle between FC and CFO ($\Delta\theta_{body}$), foot angle at FC ($\theta^{FC}{}_{foot}$), foot angle at CFO ($\theta^{CFO}{}_{foot}$), 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 [36] and slipping [37]. 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 3.a). The center of trunk was found using anthropometric tables based on the cervical marker and mid-hip joint centers [38]. The mid-hip joint centers were found using Bell's Method and the ASIS and PSIS markers [39]. 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 3.b). The foot placement was calculated as the anterior/posterior distance (y-direction, Figure 3.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.

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.

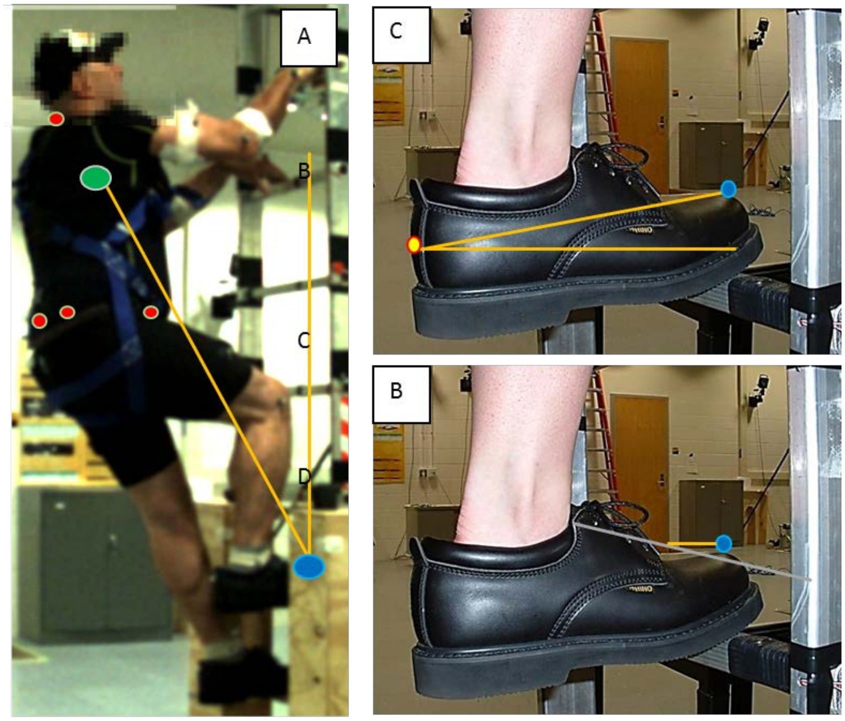


Figure 3: Measurements of body parameters: (A) Body Angle (B) Foot Angle (C) Foot Placement.

G.1.2. 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 4) confirming H1.1. Slip outcomes were not significantly influenced by hand positioning ($p=0.31$)(Figure4) 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 4).

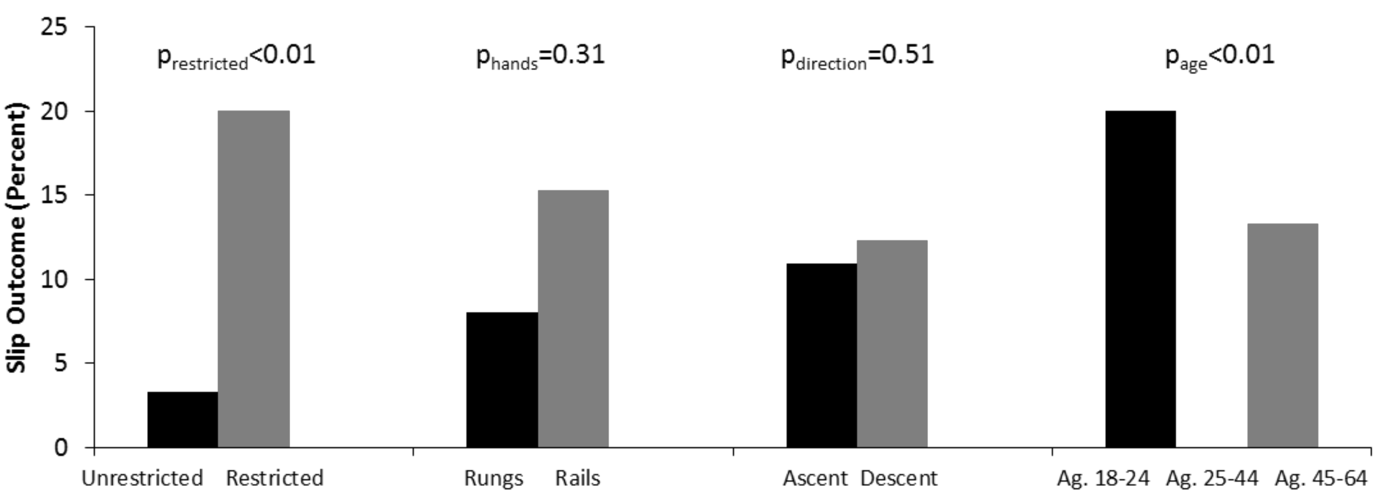


Figure 4: Effects of toe gap restriction, hand positioning, climbing direction and age group on risk of slipping. Numbers represent the percentage of exposures to the slippery rung that led to the foot slipping off of the rung.

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 (Figure 5 & 6, Table 2). 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 ($\Delta\theta_{foot}$, $p<0.05$) (Figure 5 & 6, Table 2). 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 2). None of the other biodynamic variables were statistically significant.

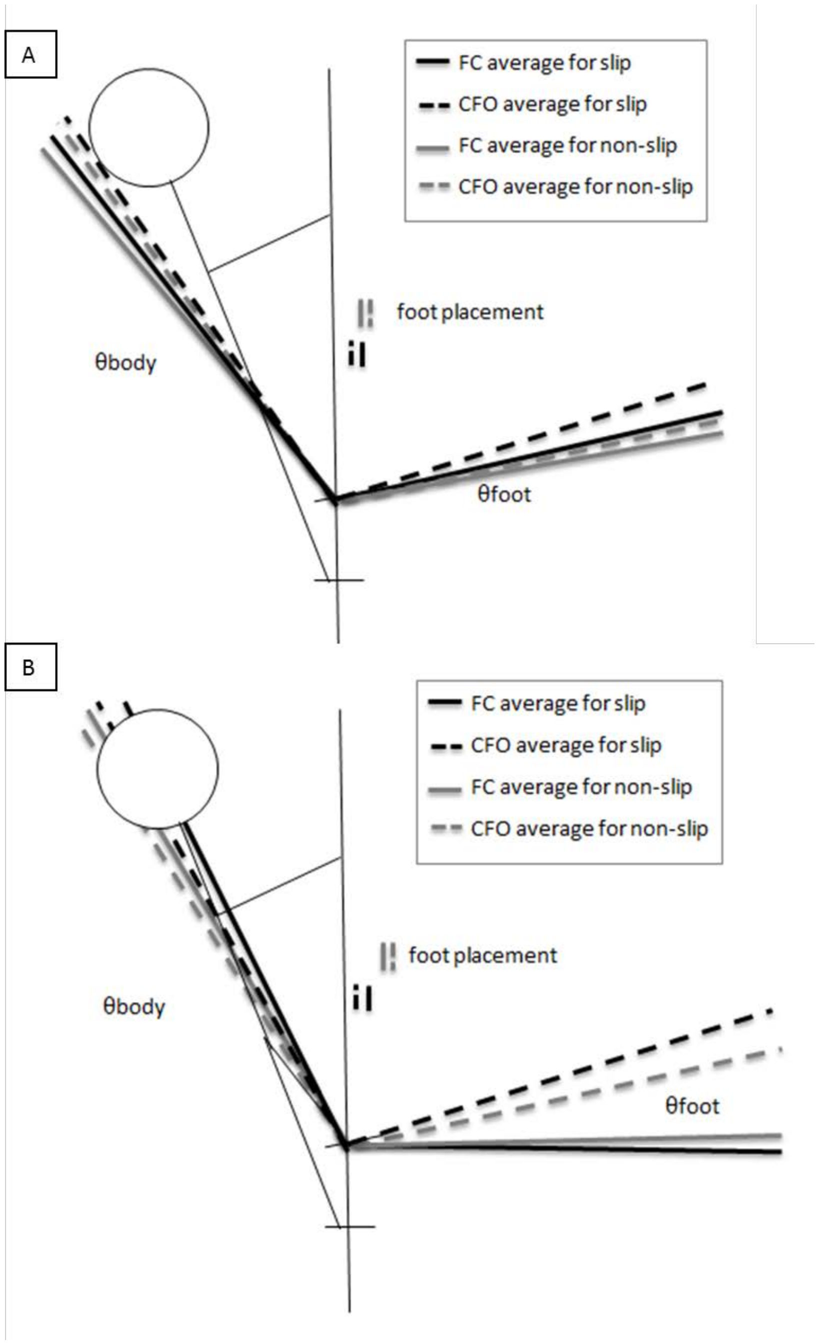


Figure 5: Average body angle (θ_{body}), foot angle (θ_{foot}) and foot placement for slip (black lines) and non-slip (grey lines) climbs at FC (solid lines) and CFO (dashed lines) during (A) ascent and (B) descent.

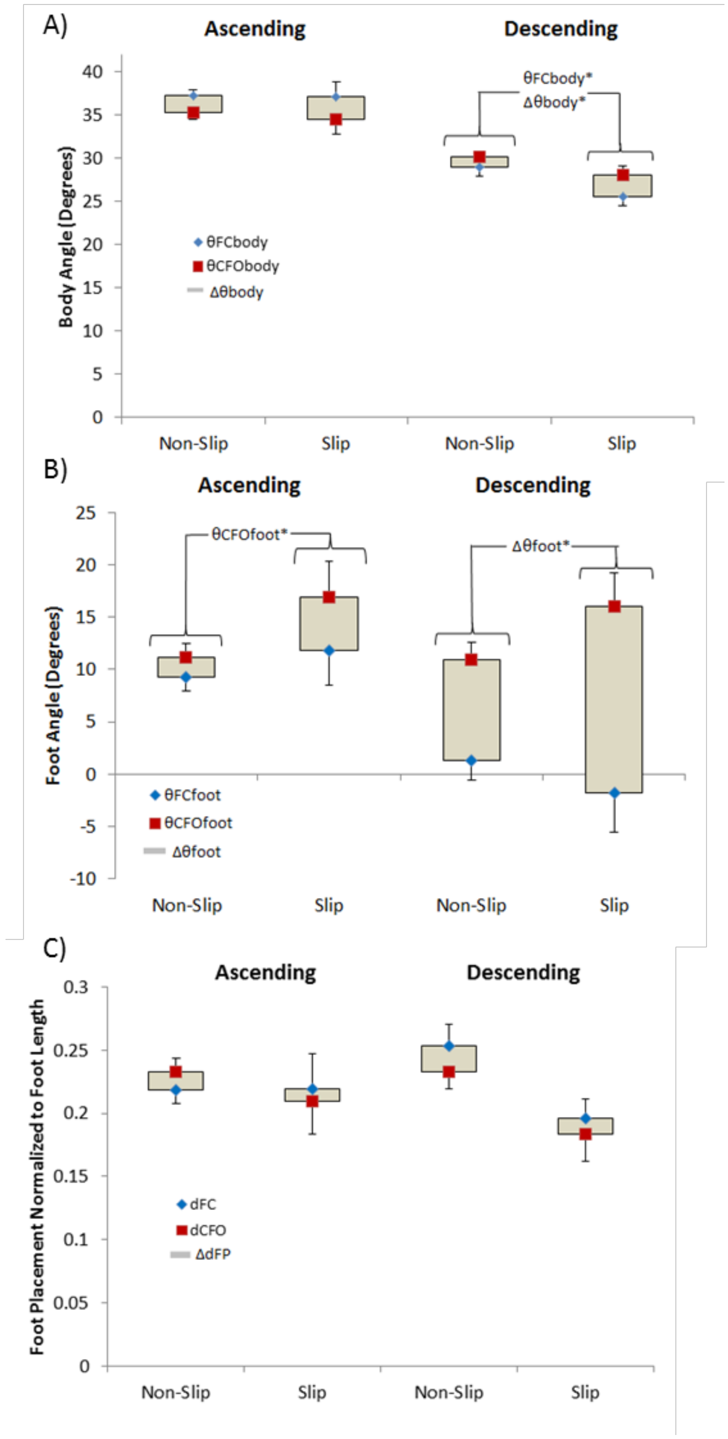


Figure 6: (A) Body angle (B) Foot angle (C) Foot Placment at foot contact (FC) and contralateral foot-off (CFO) and change between FC and CFO: Ascending (left) Descending (right). Foot contact is denoted by the blue triangle. Contralateral foot-off is denoted by the red square. Error bars off the symbol 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.

Table 2: Mean (standard deviation) on ascending (A) and descending (B) 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} $p<0.05$

G.1.3. 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 [40] and greater break-away strength is achievable when grasping horizontal surfaces rather than vertical surfaces [24].

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 [25, 41, 42] due to reduced strength, slower response times [43] and changes to their gait patterns [42]. 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 5). 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 your feet are progressing to a rung that is below you and is more obstructed from your 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 [25]. 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 [19]. 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.

G.2. Scientific Report #2: Biomechanical Response to Ladder Slipping Events: Effects of Hand Placement

G.2.1. Methods

G.2.1.1. Subjects

Fifteen slips, which were collected from eleven experienced ladder climbers, were analyzed in this study. The data were taken from a larger study of thirty-two participants [2] and part of the results of this study were previously published in proceedings for a scientific conference [40]. Only perturbations where the foot completely slipped off of the rung were included in order to focus this research on severe ladder slips. In addition, one subject who slipped was excluded because her climbing style was fundamentally different from the climbing styles of the other subjects (i.e., subject put both feet and both hands on each rung before ascending to the next rung whereas all other subjects alternated their feet on each rung). Subjects that were included in this analysis were between the ages of 18 and 61 (7 male, 4 female) and were recruited from industry sectors where ladder climbing is common, including roofing, firefighting and divers. To qualify as an experienced climber, potential participants needed to reply "yes" to a question that asked if they climbed ladders regularly. Exclusion criteria included weight over 113.4 kg, pregnancy, and musculoskeletal, neurological or balance disorders or injuries that would influence or prevent ladder climbing. Testing was approved by the University of Wisconsin-Milwaukee Institutional Review Board and informed consent was obtained from every subject.

G.2.1.2.Procedures and Data Collection

Subjects were fitted with shoes, athletic clothing and a safety harness. Forty-six passive reflective markers were placed on anatomical landmarks of the subject including the toes (dorsal side of shoe tips), the heels and the third metacarpal joints. EMG recordings from five muscles were collected bilaterally using ten double differential electrodes (Trigno ®, Delsys Inc., Boston, MA) with a built-in bandwidth filter (20-500 Hz). Bilateral muscles of interest included: biceps, triceps, anterior deltoid, semitendinosus and the vastus lateralis. The upper extremity muscles were consistent with the upper-arm muscles that respond to a handle perturbation [44] and the lower extremity muscles were consistent with those that respond to ground-level slips [43]. Prior to electrode placement, the skin was cleared of any excess hair and cleaned with an alcohol prep pad. The electrodes were placed parallel to the muscle fibers over the muscle belly, per the manufacturer's instructions [45]. EMG signals, sampled at 1000 Hz, were checked prior to testing to ensure a good quality signal.

Subjects were randomly assigned to two climbing styles based on hand position (rail vs. rung) and foot clearance conditions (restricted versus unrestricted), described in Pliner et al. [2]. For the restricted toe clearance condition, a wood board was placed at a distance of 25% of the subjects' foot length from the rung on the side of the ladder opposite to the subject. Most of the slips occurred during the restricted toe clearance condition and, therefore, this variable is not considered further in the present study. A belaying system, including a belayer, spotter, harness and impact mat, was used to ensure subject safety. The ladder consisted of 12 rungs placed 300 mm apart [22]. The fourth rung from the bottom was encased in lockable bearings so that it could be locked in place for non-slipping trials or allowed to freely spin for slipping trials. To establish a baseline for each climbing strategy, the subjects performed 5 to 6 non-slip climbing trials with the fourth rung locked in place. One perturbed slip trial was then conducted with the fourth rung allowed to freely spin. The subject then switched to the second assigned climbing style, completed an additional set of 5 to 6 baseline trials, and then experienced a second slip. The subjects were unaware of the status of the lockable rung throughout the test session. Also, subjects could slip during ascent and descent. A 13 camera Motion Analysis Corporation system (Motion Analysis Corp, Santa Rosa, CA) acquired marker position data at 100Hz, which were time-synchronized with the EMG data.

G.2.1.3.Data Analysis

Data from at least 3 unperturbed trials were used to quantify the baseline muscle activity. Unperturbed trials were only included in the baseline average if they had similar climbing gait patterns as the perturbed (slip) trial (i.e., started on the same foot and had the same hand-foot coordination) since several studies have noted significant inter- and intra- subject climbing styles [46, 47].

An RMS signal smoothing algorithm with a 30 ms moving window was applied to the filtered EMG signals for the baseline and slip trials [48-50]. Data from each of the baseline trials were interpolated over 1000 data points from foot contact of the slip foot to the next foot contact (i.e., the foot contralateral to the slip). After averaging the interpolated data, the data were interpolated again at the sampling frequency (1080 Hz) between heel contact (t = 0) and the average climbing cycle time (contact time of the foot stepping on the slip rung to contact time of the foot contralateral to the foot stepping on the slip rung) to get time-series data that could be compared against data from the slipping trial. The perturbed slip trial RMS EMG signal, which was filtered and smoothed using the same methods as the baseline trials, was compared to the baseline average in order to determine when the muscle activation patterns from the slip exceeded baseline activity. The motor patterns from the perturbed trial were not time-normalized to make them directly comparable to baseline time-series data.

This approach was used to determine the onset time when muscles switched from their baseline motor patterns to the recovery response motor patterns following an unexpected perturbation [51-53]. Muscle response onset time was quantified as the time point after slip onset when the smoothed EMG signal exceeded the average baseline by more than two standard deviations for a period of at least 50 ms, similar to other methods used to assess responses to slips [51]. Only muscle activations that occurred at least 30ms after slip initiation were included due to the time that is required to process sensory information and initiate a motor response. The activation period of interest contained the peak muscle activity in order to focus on the greatest magnitude of the RMS response. Previous research has indicated that the perturbed limb and the non-perturbed limb respond with similar onset times [51, 53] and preliminary analyses of the data did not reveal significant differences in muscle onset or peak times across sides of the body (i.e., ipsilateral versus contralateral to the slip). Therefore, left and right muscle times were pooled together.

Descriptive analyses were performed to explain the state of the climber at slip initiation and the experimental conditions for these fifteen slips. Categorical variables of interest at the time of slip initiation included: if the contralateral foot was in contact with a rung, and if the subject was using 3 points of contact. Additional variables of interest included climbing direction (ascent versus descent) and toe clearance (restricted versus non-restricted toe gap space).

Events (hand/foot contact, hand/foot off and slip initiation) were determined based on kinematic data using the toe and hand (third metacarpal) markers. The events of hand/foot contact were identified based on the first time when the resultant hand/foot speed fell below 10% of its peak speed whereas hand release/foot off were the first time point when it exceeded 10% of its peak speed.

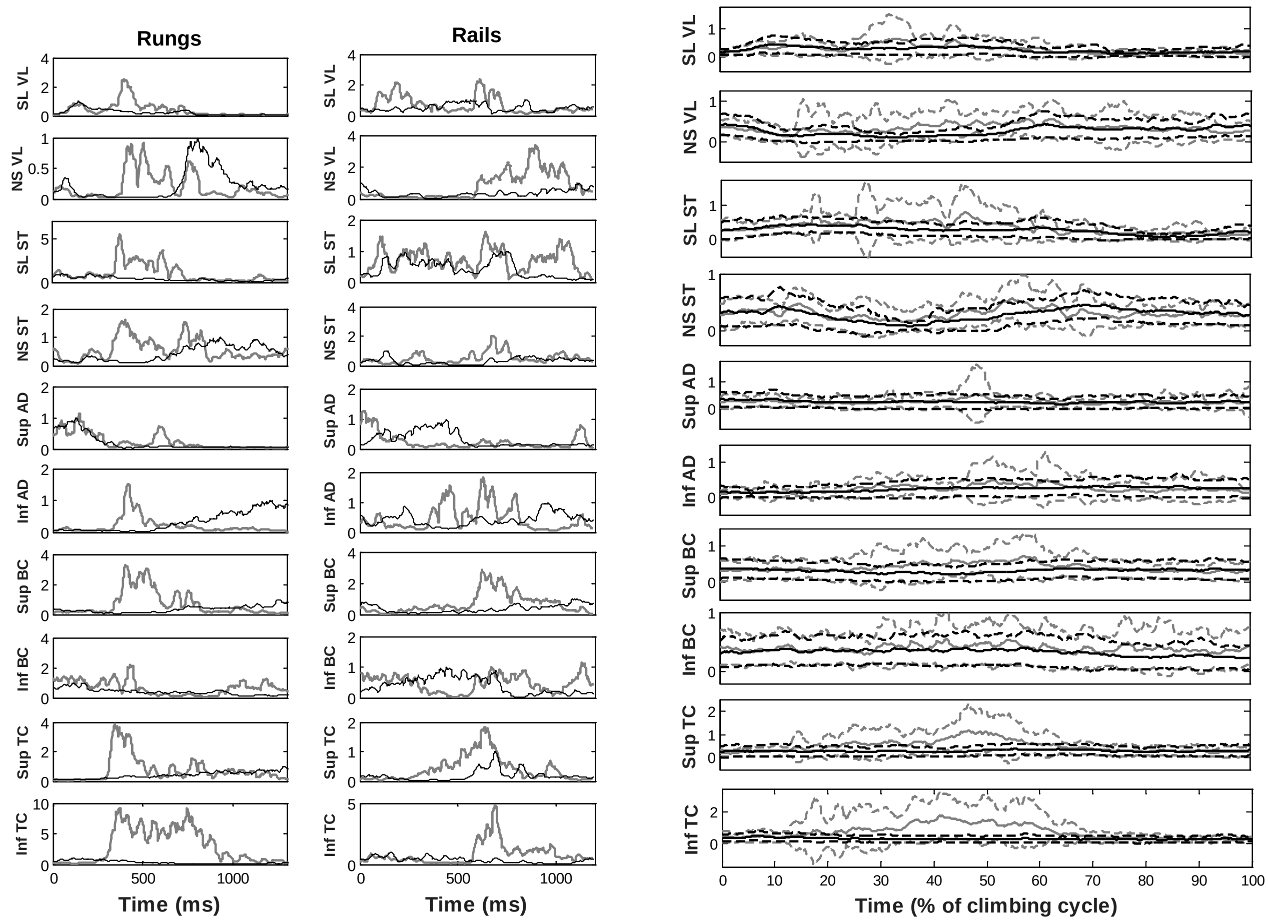
G.2.1.4.Statistical Analysis

Mixed-methods repeated-measures ANOVAs were used to assess the effects of handhold (rungs vs. rails, between-subject factor) and muscle (within-subject factor) on muscle onset and peak activity times. Onset and peak activity times were transformed with a log function to achieve normality. Similarly, the timing of the temporal events during the slip response was assessed using a mixed-methods repeated-measures ANOVA model. The timing of the event was the dependent variable, while the independent variables included a nominal variable of the event category (within-subject factor) and the handhold (between-subject factor). The event categories included the hand detaching from the ladder rung or rail; the hand reconnecting with the ladder rung or rail; the foot contralateral to the slip stepping off of a rung preceding the slip rung; the foot contralateral to the slip being reestablished back on to a ladder rung; the slipping foot falling off of the rung; and the slipping foot being reestablished back on to a ladder rung. Preliminary analyses revealed no differences between ascent and descent in the timing of EMG onset, peak, or event times and therefore, ascent and descent slips were pooled together. In the case that muscle or event was significant, post-hoc Tukey's HSD tests were performed to determine the muscle or event timing sequences that were significantly distinct. An significance level of 0.05 was used for all analyses.

G.2.2. Results

G.2.2.1.Biomechanical Response

Slip EMG activity was found to deviate from baseline activity (Figure 7A) but the only consistent deviation across subjects was an increase in triceps activity during the slip relative to the baseline trials (Figure 7B). The handhold technique was found to affect the timing of muscle activation onset (p=0.038) and the peak activation level (p=0.049) (Figures 8 and 9). Specifically, the average time delay between foot contact and muscle onset was shorter for rung placement (446 ms +/- 212 ms standard deviation) than for rail hand placement (726 ms +/- 306 ms) (Figure 8). Similarly, peak activation times occurred earlier when grasping the rung (518 ms +/- 217 ms) than the rail (816 ms +/- 321 ms) (Figure 9). Significant differences in onset (p=0.008) and peak activity time (p=0.019) were found across the muscles (Figures 8 and 9). The triceps onset time (509 ms +/- 205 ms) was earlier than the biceps (718 ms +/- 416 ms) and the anterior deltoid muscles (764 ms +/- 337 ms) (Figure 8). Peak activity also occurred earlier for the triceps (601 ms +/- 215 ms) than for the biceps (778 ms +/- 427 ms) (Figure 9). Age, height and weight characteristics (Table 3) were not significantly different between the rung and rail hand placement groups.



*Note that the y-axis scales are not consistent across all muscles.

Figure 7: A: Representative RMS muscle activity (normalized to the peak RMS muscle activity of the unperturbed trials) from one slip using rung hand placement (left column) and from one slip using rail hand placement (right column). The thin black line represents the average muscle activity of the unperturbed trials and the bold gray line represents muscle activity during the slip trial. B: Averaged baseline (black) and unexpected slip (bold gray) activity across subjects. The solid lines represent the mean activity and the dashed lines demonstrate +/- 1 standard deviation from the mean. For the representative and averaged plots, the slip is initiated at time = 0. VL = vastus lateralis, ST = semitendinosus, AD = anterior deltoid, BC = biceps, TC = triceps. “Inferior” (Inf) refers to the hand at a lower position relative to the “Superior” (Sup) hand at slip initiation. “Slip” (SL) refers to the slipping leg, while “Non-Slip” (NS) refers to the leg contralateral to the slip.

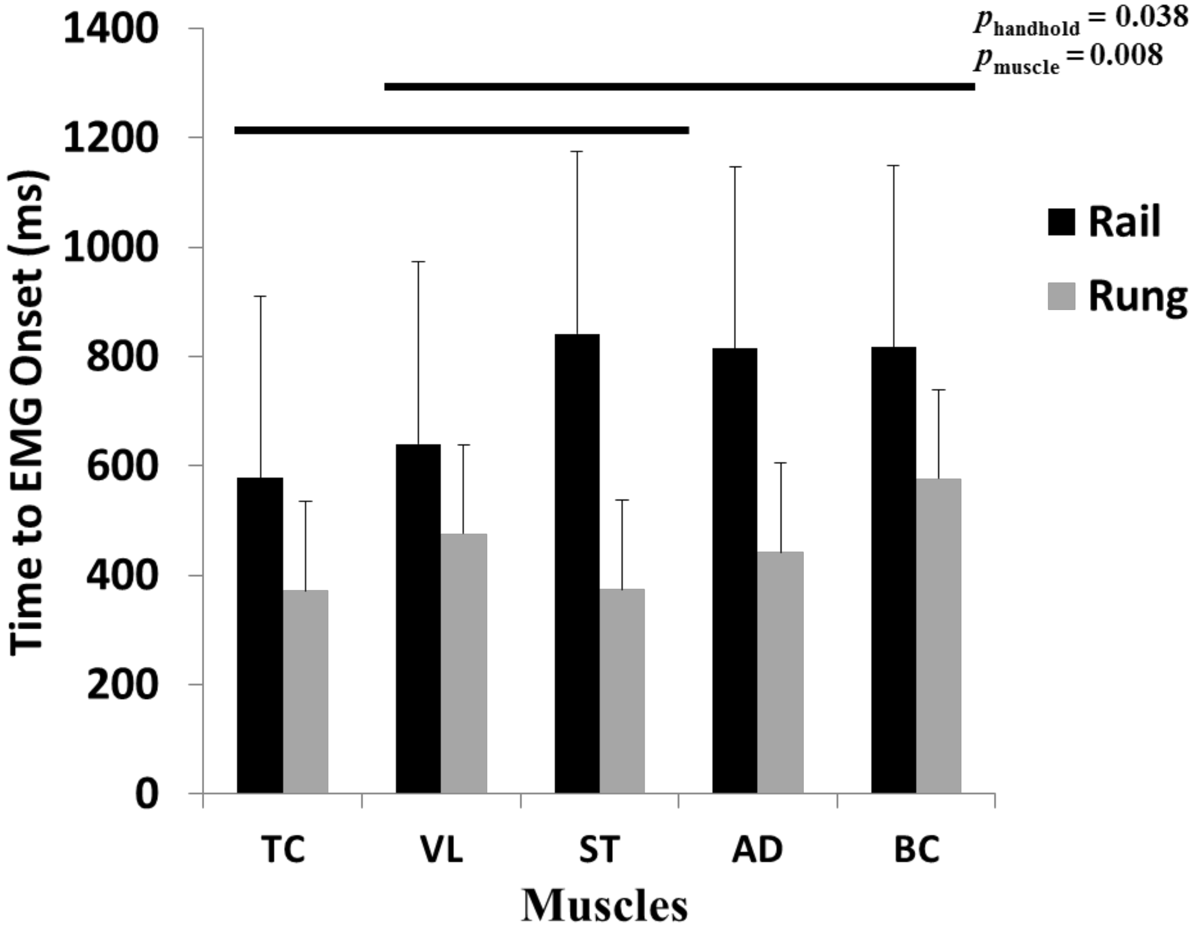


Figure 8: Average time from slip initiation to muscle onset for each muscle, during rail (black) and rung (gray) hand placements. Muscles that are not connected by the black bar are statistically different (p<0.05).

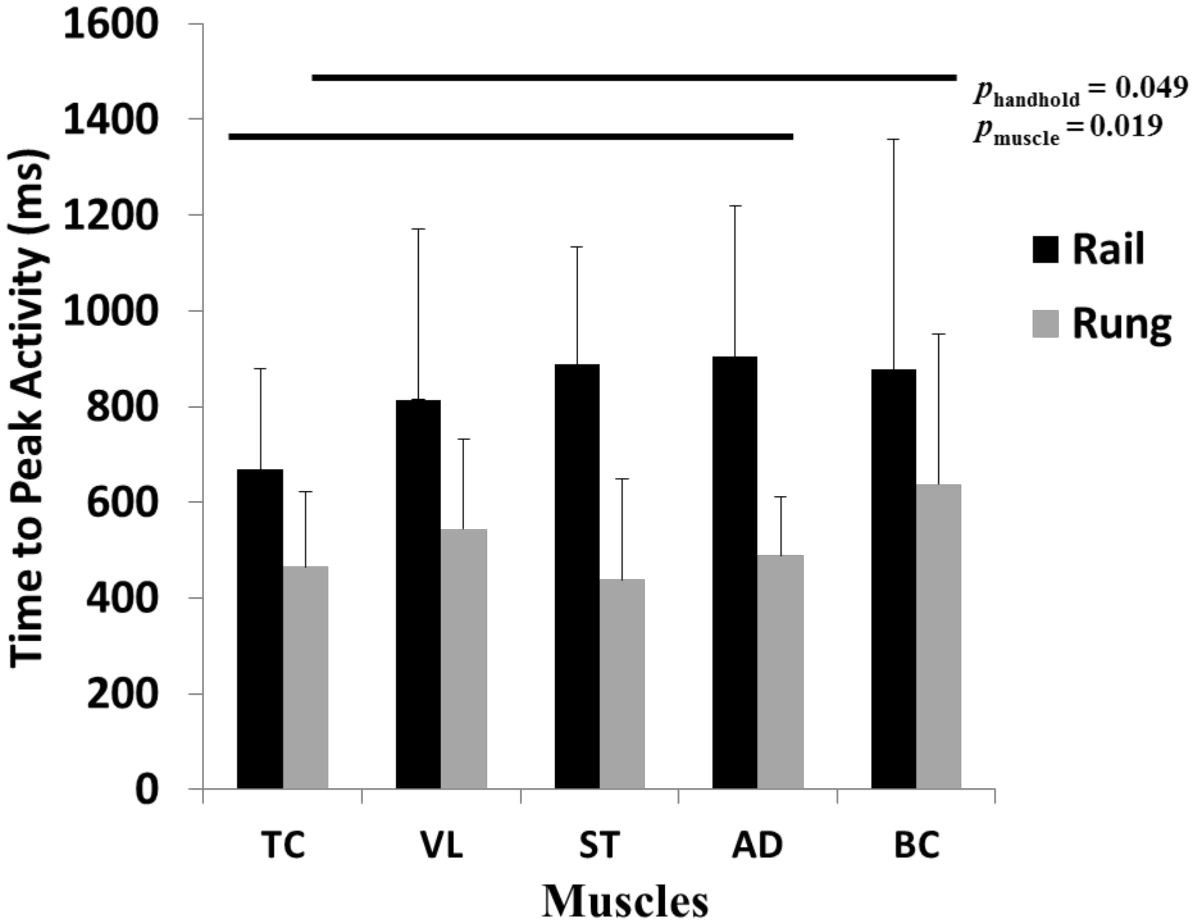


Figure 9: Average time from slip initiation to peak muscle activity for each muscle, during rail (black) and rung (gray) hand placements. Muscles that are not connected by the black bar are statistically different ($p<0.05$).

Table 3. Subject Characteristics

Subject	Hand Placement	Age (yrs)	Height (cm)	Weight (kg)	Foot Length (cm)	Gender
1	Rung	50	177.1	82.3	27	M
2 (twice)	Rung	18	167.5	62.2	22	M
3	Rung	22	169	67.8	26	M
4	Rung	18	179	81.4	29	M
Avg(Stdev)		27.0(15.4)	173.2(5.7)	73.4(10.0)	26.0(2.9)	0 F / 4 M
Subject	Hand Placement	Age (yrs)	Height (cm)	Weight (kg)	Foot Length (cm)	Gender
2	Rail	18	167.5	62.2	22	M
5 (twice)	Rail	23	186	111.9	30	M
6	Rail	19	173.5	67.5	26.5	M
7	Rail	45	176	87.3	28.5	F
8 (twice)	Rail	61	155	58.4	25	F
9	Rail	23	176	107.0	26	F
10	Rail	19	170	78.0	26	F
11	Rail	56	167	79.8	27.5	M

Avg(Stdev)		33.0(18.0)	171.4(9.0)	81.5(19.7)	26.4(2.4)	4 F / 4 M
GROUP						
Avg(Stdev)	4 Rg / 9 Rl	32.2 (17.0)	172.4(8.1)	80.3(17.0)	26.7(2.2)	4 F / 8 M

G.2.2.2.Sequence of Events

The timing across the different events were found to be statistically different ($p<0.001$). Post-hoc Tukey HSD test revealed that multiple events were statistically different (Figure 10). The timing of the slip can be considered in two phases: the time when the foot slips off of the ladder (i.e., the onset of the perturbation) and the time that the limbs reestablish back on the ladder (i.e., the attempted recovery). Typically, the foot slipped off of the ladder around the time when the hand moved off of the ladder and the non-perturbed foot left the ladder. After the slip, the limbs reestablished themselves back on the ladder in the following order: the hand that was in motion, the foot contralateral to the slip and then the slipping foot. The handhold type did not affect the timing of events (p = 0.133).

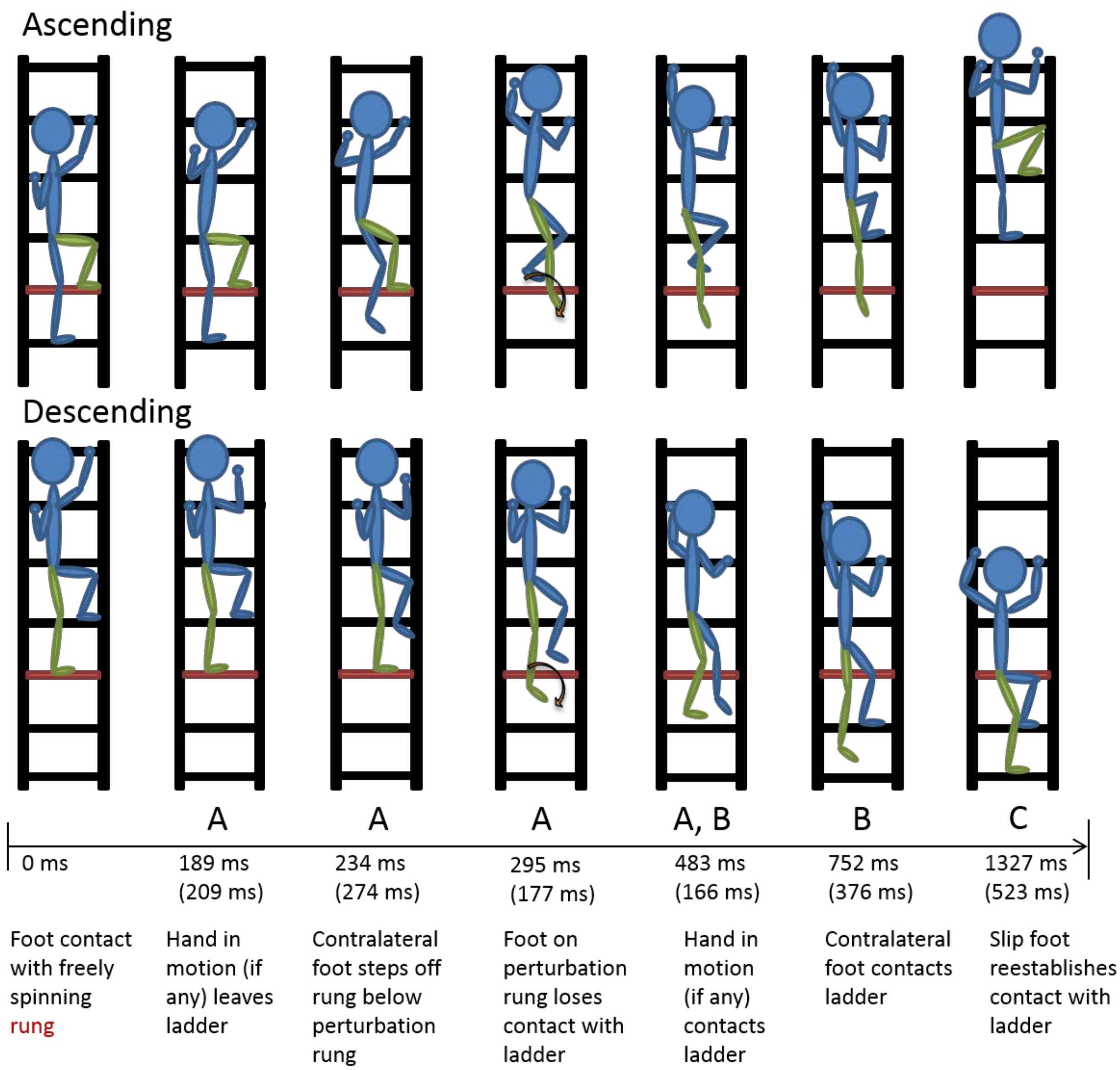


Figure 10: Timing of events during a ladder climbing slip for ascent and descent. Climbing direction did not affect the timing of events and therefore only the times averaged across all slips are shown. Timing

means (standard deviations) are listed for each event. Events not connected by the same letter are significantly different (p<0.05).

G.2.2.3. Descriptive Analysis

Subjects varied in their climbing state at slip initiation (Table 4). In fourteen of the fifteen slips, the slip occurred after the contralateral foot was no longer in contact with the ladder. Only five of the fifteen slips occurred when a subject was using three points of contact at slip initiation. Most of the slip recoveries were observed during climbing with restricted toe clearance and about half were experienced during ascent.

Table 4. Descriptions of ladder condition and climber state at slip initiation

	Hand Placement	
State of climber at slip initiation	Rungs (5 total)	Rails (10 total)
Contralateral foot in contact with rung (No)	0 (5)	1 (9)
Subject using 3 points of contact (No)	3 (2)	2 (8)
Ladder Testing Condition		
Ladder toe clearance: Unrestricted (Restricted)	0 (5)	2 (8)
Climbing Direction: Ascend (Descend)	2 (3)	5 (5)

G.2.3. Discussion

The primary goals of this study were to assess the impact of grasping rungs versus rail on muscle activation onset and peak activity timing in response to a ladder slip and to characterize the events that follow a ladder slip. The study revealed that muscle onset times were on average 39% (280 ms) faster when grasping the rungs than when grasping the rails. Slipping typically occurred around the time that both the foot contralateral to the slip and a hand had left their respective rungs, indicating that slips occur when a person has fewer than three points of contact and is most vulnerable.

The faster response experienced while grasping the rungs compared with the rails may be because the motor system was already cued to execute a grasping response while holding on to the rungs whereas a change in grasping strategy was required when grasping the rails. Grasping the rails may require climbers to switch their grip strategy after the perturbation. Armstrong et al. reported that rail use resulted in a more medially-directed hand force than rung use [20], which can be generated by hooking the fingers around the outside of the ladder. However, a power grip is required to generate the friction forces required to oppose vertical forces during a fall [23, 24]. The utilization of non-preferred grip strategies has previously been shown to increase response time by up to 200 ms when compared to preferred grip strategies since additional motor planning is required to execute non-preferred gripping [54]. Thus, the change in strategy from a hook grip to a power grip during rail climbing may have required more motor planning and response time. Regardless of the mechanism that causes increased latencies for rail climbing, the degree to which the motor response was delayed (~280 ms) is substantial. For example, a reduction in postural response latencies of just 28 ms after an agility training program was associated with a 40% reduction in fall events during platform perturbations in stroke patients [3]. The increased latency when grasping the rails likely has a negative impact on subjects' ability to recover and may increase fall risk.

The triceps were the first muscle to activate and reach peak activity after slip onset. This response may be analogous to previous research where the response to platform perturbations is characterized by an initial knee extension response followed by knee flexion response [53]. However, this finding is in contrast to the EMG activities that occur during handle stabilization tasks, where biceps and triceps have been shown to activate around the same time [44]. Potential reasons for this discrepancy may be due to different objectives by the participants between handle stabilization and ladder fall response tasks. Activating the triceps during a ladder fall event may be needed to extend the arm in order to reach for the next rung. Alternatively, extended arms also increase the potential hand force generation [55]. The similar onset and peak activity times between upper body muscles and lower body muscles is consistent with previous research that has shown a rapid, coordinated and concurrent response to slipping between the upper and lower body [51].

Another aim of the study was to quantify the timing of events after a slip is initiated in order to characterize the motor response to ladder slips. This study found that most of the slips occurred while both the foot contralateral to the slip and a hand were in motion. Therefore, the slip left the subjects with just one remaining point of contact. This finding supports the utilization of slip-prevention strategies (like three points of contact) around this phase in the climbing cycle.

A few limitations were identified in this study. For example, large standard deviations were encountered for the event timings, which is likely explained by climbing pattern differences across subjects (Table 2). Encouraging consistency across and within subjects may be needed to more precisely identify the sequencing of events and muscles after a ladder slip. Variability may also be partially explained by the lack of control regarding onset of the perturbation. Controlling the perturbation (e.g., through a motorized rung) would have likely led to a more consistent perturbation but would have reduced its environmental fidelity. Additionally, it is noted that while an equal amount of males slipped from the ladder when using rail and rung hand placements, all of the female slips from the ladder occurred during rail hand placement (Table 1). While the sample size was not large enough to test this effect statistically, additional research may be needed to better quantify the effects of gender on ladder recoveries in more detail. Also, not enough slips occurred to power an analysis to determine if EMG onset times or grasping strategies led to differences in recovery rates. Repeating this study with a larger data set confirm the relevance of response time to recovery risk after slipping from a ladder. Lastly, quantifying differences in motor patterns across different phases of the climbing cycle when aware of a slippery rung versus a non-slippery rung, similar to Capellini et al. [56], may provide insights into adaptive strategies used to avoid slipping.

G.3. Scientific Report #3: Ladder climbing factors that affect the severity of falls from ladders [Confidential]

G.3.1. Materials and Methods

G.3.1.1. Subjects

Thirty-five of forty total recruited participants between the ages of 18 and 29 years completed the study. 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).

G.3.1.2. Experimental Approach

Participants were equipped with climbing attire, footwear, shin guards and a safety harness after the mass and height of each participant were recorded. 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). Only the bilateral anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), hand, and foot 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). A vertical 12-foot custom-designed ladder was secured in the middle of the motion capture volume (Figure 11). 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 [1]. To ensure participant safety, each participant had an impact mat at the bottom of the ladder, a spotter and belayer.

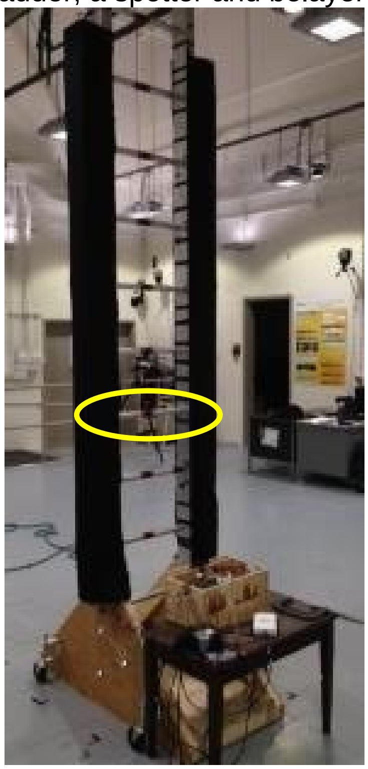


Figure 11: Custom-designed ladder. The ellipse encircles the releasing rung.

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 [2]. Participants were instructed to climb at a "comfortable but urgent pace" to simulate climbing speed of a regular busy workday.

Hand forces were measured on a separate day preceding the ladder perturbation trials. Subjects performed using a handheld hand strength dynamometer (Jamar), maximum pull exertions in three upper limb postures and breakaway exertion. The maximum pull exertions were performed at shoulder height, at full arm extension height and at a medium height that was half way between shoulder and full extension height. In the breakaway exertions, subjects held on to a rung while a motor pulled the rung away from the body [57]. Subjects were seated and secured with a belt during all exertions. These exertions were performed in three hand-rung friction conditions (CoF=0.6 for bare hand, 1.0 for rubber glove, and 0.4 for cotton glove). Both hands were tested.

G.3.1.3.Data and Statistical Analysis

G.3.1.3.1.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 (poor recovery) and a low harness force was associated with a less severe fall (better recovery). The harness force was normalized to each participant's body weight and calculated at the end of the fall. Start of fall was the time the rung was triggered to release. End of fall was the time of peak harness force between perturbation onset and the first harness force maximum after the first minimum of mid-hip joint center's vertical displacement after the start of fall [58]. Mid-hip joint centers were calculated using Bell's Method and the ASIS and PSIS markers [39]. The peak harness force within this window was used to characterize fall severity. Trials were excluded if the calculated end of fall time varied substantially from a visually-determined end of fall time (n=1/88 for ascent and n=7/87 for descent).

A mixed-measures ANOVA was performed with subject number (random), gender, perturbation number (nominal), climbing direction and glove condition as the 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 3.1.1 would be confirmed if females had significantly higher harness forces than males. Hypothesis 3.1.2 would be confirmed if missteps during ladder descent resulted in significantly higher harness forces than ladder ascent. Hypothesis 3.1.3 would be confirmed if high friction gloves resulted in significantly lower harness forces compared to the bare hand and low friction glove conditions.

G.3.1.3.2.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 (HP) were observed: HP2-Hand continued to next rung as planned (moving two rungs up during ascent or two rungs down during descent from starting position); HP1-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); HP0-Hand momentarily elevated from starting position before re-grasping the same rung; HPN-Hand did not move. Trials where both hands released the rung or the moving hand did not grasp the rung before end of fall were excluded (n=2/87 for ascent and n=3/80 for descent). Trials where participants had an unusual climbing pattern (i.e., moved their hands one rung as opposed to two rungs per movement) or changed their climbing pattern from previous trials were excluded (n=2/87 for ascent and n=20/80 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 due to lack of power.

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 (FP) were observed: FP2-Two feet hit the top of the rung(s) and reestablished foot placement on the rung(s); FP1-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); FP0-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 (onset/offset) times at the start of fall and at the end of fall. Hand and foot contact times were determined from the hand (third metacarpal) and toe kinematic data. Hand/foot onset was the first time the hand/foot speed fell below 10% of the hand/foot peak velocity during travel to the next rung. Hand/foot offset was the first time the hand/foot speed exceeded 10% of the hand/foot peak velocity [1].

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 3.2). 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 3.2.1 would be confirmed if harness forces across hand responses were significantly different. Hypothesis 3.2.2 would be confirmed if reestablishing foot placement back onto the rung resulted in significantly lower harness forces.

Post-hoc analyses were utilized to determine if hand offset time, hand contact time, and hand movement times were different across the three hand placements where the hand released the rung. Specifically, ANOVA methods were utilized to determine if the time of hand off relative to perturbation onset, hand contact time relative to perturbation onset and hand movement time (time between hand off and hand contact) were different across the three hand placements where the hand released the rung (HP0, HP1 and HP2).

G.3.1.3.3. Analysis 3

Peak hand forces were calculated for each of the glove conditions (high friction, low friction and bare hand) and for each of the five testing conditions (Jamar, shoulder height, medium height, full height and breakaway strength). An ANOVA was used with the peak force as the dependent variable. The independent variables were subject (random), glove conditions, testing conditions and the interactions. In addition, an ANOVA was used to determine if individual hand strength (averaged across both hands for all three gloves) was predictive of fall severity. Ten different statistical models were generated (five hand strength testing methods by two climbing directions) with harness force as the dependent variable. The independent variables for each condition were subject (random), hand strength and any significant covariates identified in Analysis 1 and 2. Hypothesis 3.3 would be confirmed if hand strength measures had a significant effect on harness forces.

G.3.2. Results

G.3.2.1. Analysis 1

Hypothesis 3.1.1 and 3.1.2 were confirmed, but not hypothesis 3.1.3. Females had significantly higher harness forces than males ($p = 0.016$, $F = 6.61$). Specifically, normalized harness forces were 0.23 and 0.38 for males and females, respectively. The harness forces for descending perturbations were more than double the value of ascending perturbations ($p < 0.001$, $F = 104.1$). The average (standard deviation) harness force for bare hands, high friction and low friction gloves were 0.28 (0.24), 0. 27 (0.26), and 0.31 (0.28), respectively. Glove condition did not significantly affect harness force ($p = 0.886$, $F = 0.1$). Harness force did not significantly change across the six perturbations ($p = 0.118$, $F = 1.7$) (Figure 12).

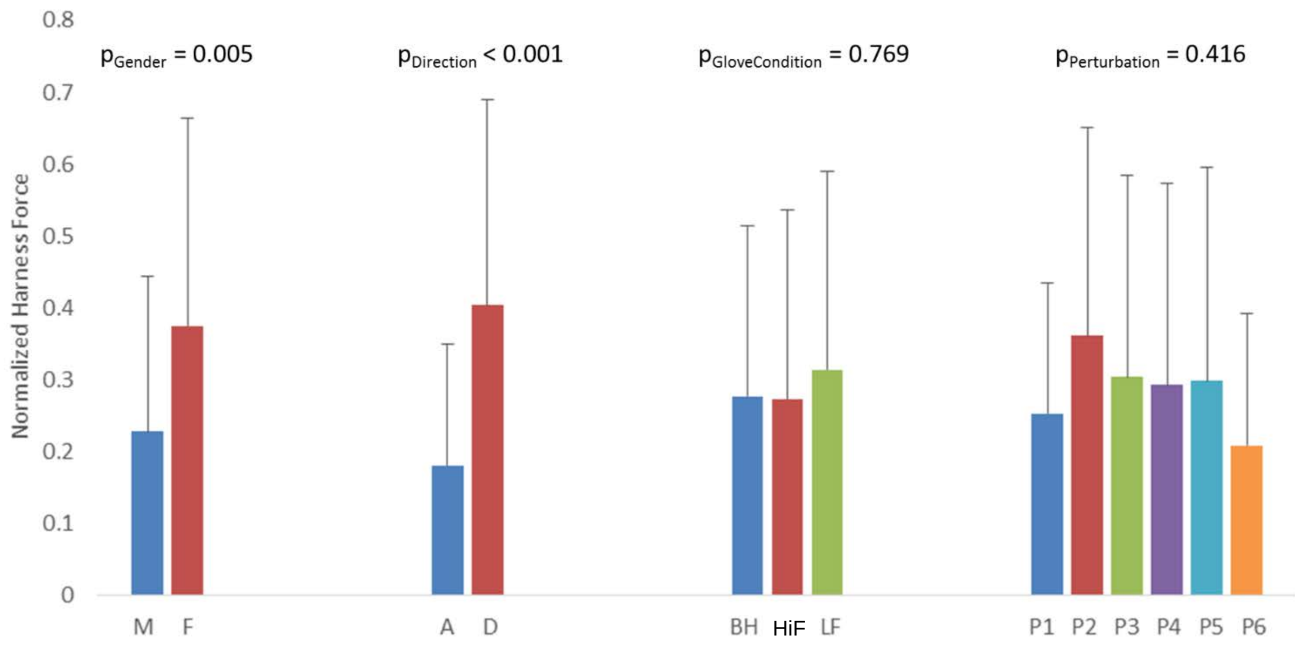


Figure 12: Average harness force normalized to body weight for males (M) vs. females (F), ascend (A) vs. descend (D), bare hand (BH), high friction (HiF) vs. low friction (LF), and perturbations one (P1) through six (P6).

G.3.2.2. Analysis 2

Hand and foot placement after perturbation onset varied across the four hand placements and three foot placements. During ascent HP2 was utilized in 31% of trials; HP1 was utilized in 10% of trials; HP0 was utilized in in 14% of trials; HPN was utilized in 45% of trials. (Table 5). During descent, HP2 was utilized in 68% of trials; HP1 was utilized in 18% of trials; HP0 was utilized in 11% of trials; HPN was utilized in 4% of trials (Table 5).During ascent, FP2 was utilized in 20% of trials; FP1 was utilized in 46% of trials; FP0 was utilized in 34% of trials (Table 5). During descent, FP2 was utilized in 17% of trials; FP1 was utilized in 54% of trials; FP0 was utilized in 30% of trials.

Table 5: Percentages of hand and foot responses utilized after a ladder perturbation.

Response	HP2	HP1	HP0	HPN	FP2	FP1	FP0
Ascend	31%	10%	14%	45%	20%	46%	34%
Descend	68%	18%	11%	4%	17%	54%	30%

Hypotheses 3.2.1 and 3.2.2 were confirmed for perturbations during ascending ladder climbs. Hand placement had a significant effect on fall severity ($p = 0.003$, $F = 5.2$). Participants who interrupted the hand's planned path of motion, landing only one rung above the starting position (HP1) had significantly higher harness forces than the hand responses where the hand re-grasped the starting rung (HP0) or continued to the next rung as planned (HP2) (Figure 13). HP1 had the longest hand movement time and the latest hand contact time after the perturbation onset (Figure 14). Foot placement also affected fall severity ($p < 0.001$, $F = 11.6$). 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 (Figure 15). Gender was added to the model since it was identified as a significant covariate in Analysis 1. However, this variable was no longer significant when hand placement and foot placement were included in the model ($p = 0.083$, $F = 3.2$).

Hypothesis 3.2.1 was confirmed, but Hypothesis 3.2.2 was not confirmed for perturbations during descending ladder climbs. Hand placement was found to influence fall severity ($p < 0.011$, $F = 4.3$) but feet placement did not have a significant effect ($p = 0.944$, $F = 0.9$). Hand placement HPN was not included in the analysis for descending climbs because the hand response occurred in less than 5% of trials. Participants who re-established their grasp with the starting rung (HP0) and grasped one rung lower (HP1) had lower harness forces than those who grasped two rungs lower (HP2) (Figure 13). HP2 was typically associated with a hand release time preceding perturbation onset and a longer hand movement time than the other hand placements (Figure 14). Gender was not a significant covariate during descending perturbations ($p = 0.094$, $F = 3.2$).

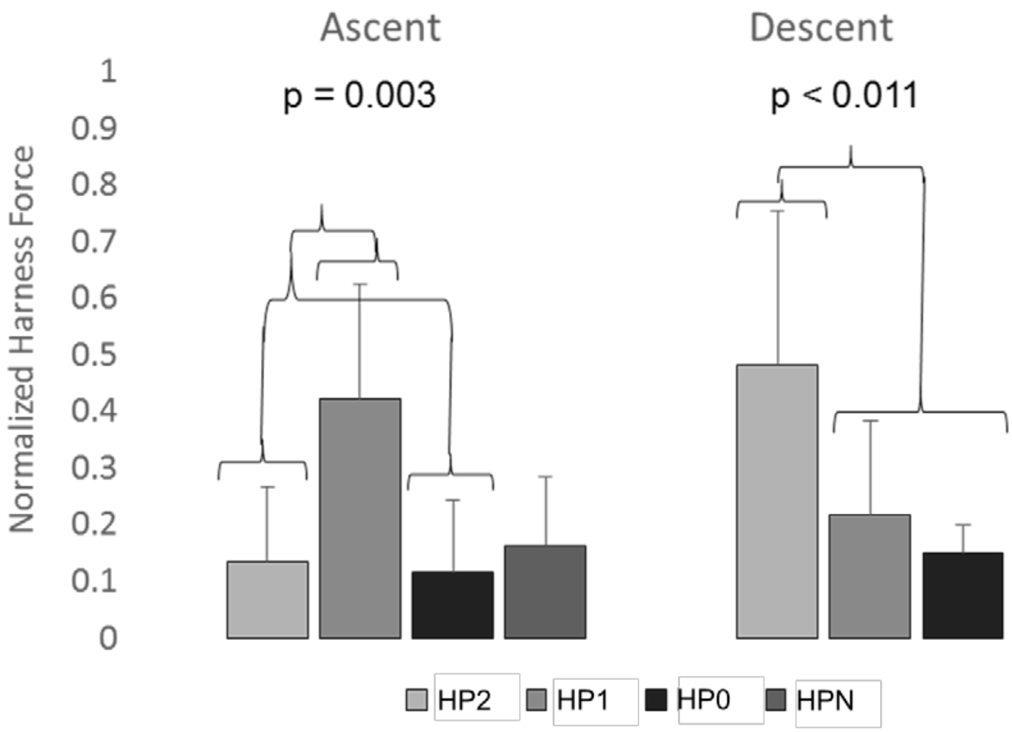


Figure 13: Average harness force normalized to body weight for hand placements during ascent (left) and descent (right) ladder fall recovery. Error bars represent standard deviations. Hand placements divided by brackets are significantly different (p<0.05).

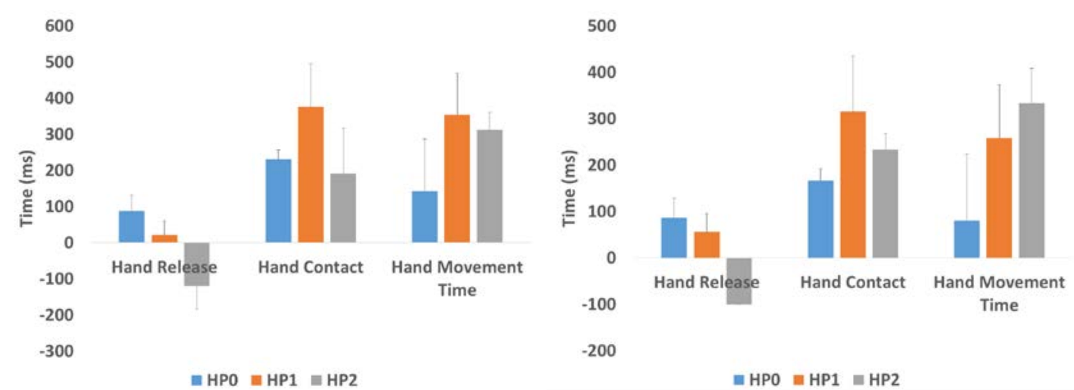


Figure 14: Average hand release, hand contact and hand movement times across each of the three hand placements. Error bars represent standard deviations.

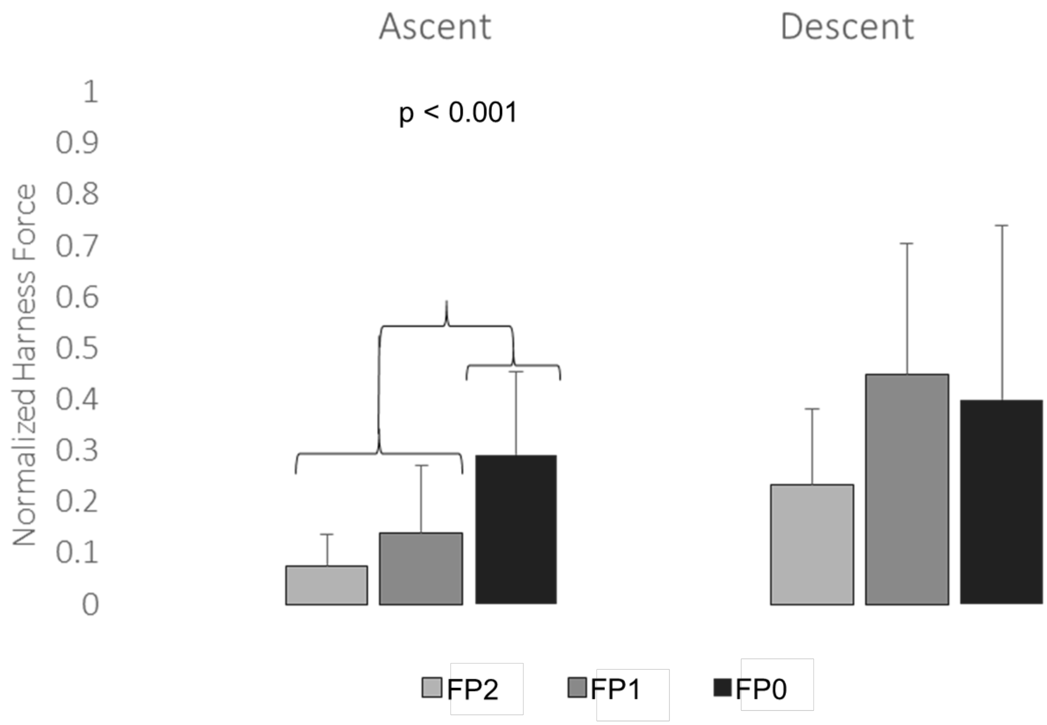


Figure 15: Average harness force normalized to body weight for feet placements during ascent (left) and descent (right) ladder fall recovery. Error bars represent standard deviations and foot placements separated by brackets are significantly different ($p<0.05$)

G.3.2.1. Analysis 3

Hand strength was affected by the testing condition ($p<0.001$, $F=76.2$), glove condition ($p<0.001$, $F=12.5$), and their interaction ($p<0.001$, $F=19.6$). Larger forces were observed for break-away and full height pulling, followed by medium height pulling and then Jamar strength and shoulder height (Figure 16). The HiF gloves and BH conditions had higher forces than the low friction gloves. Also, the HiF gloves led to an increase in breakaway strength and medium height pull strength but a decrease in Jamar strength.

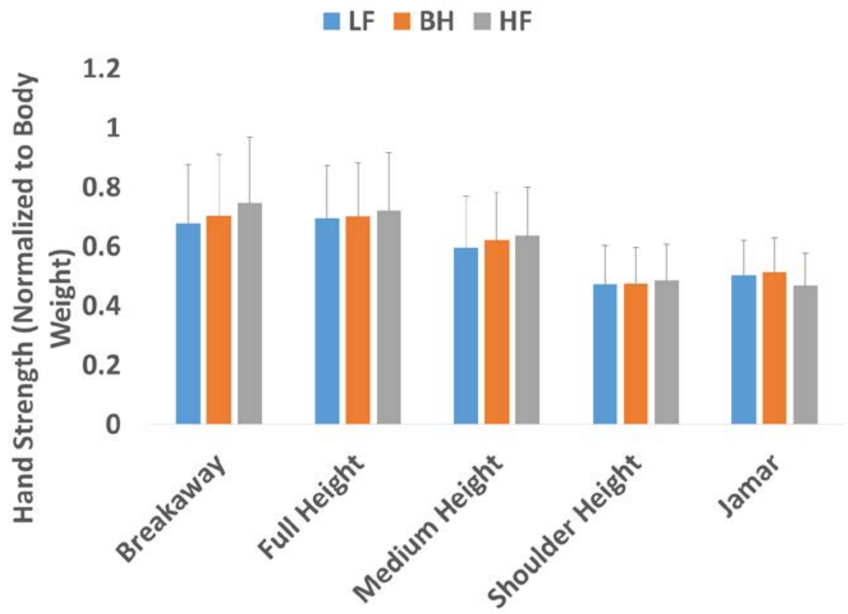


Figure 16: Effects of testing technique and glove condition on strength. Error bars represent standard deviations.

Certain hand strength measures were significantly correlated with fall severity during ascent but not with descent. Jamar hand strength (p = 0.035, F = 5.0), pull strength at full height (p = 0.0159, F = 6.6) (Figure 17) and pull strength at medium height (p = 0.049, F = 4.3) had a significant effect on peak harness forces during ascent. Pull strength at shoulder height (p = 0.311, F = 1.1) and breakaway strength (p = 0.11, F = 2.7) did not significantly affect break-away forces during ascent. None of the hand forces were predictive of peak harness forces during descent (Breakaway: p = 0.31, F = 1.1; pull strength- shoulder height: p = 0.36, F = 0.9; pull strength-medium height: p = 0.11, F =2.7; pull strength-full height: p = 0.14, F = 2.4; Jamar: p = 0.16, F = 2.1). Adding hand strength variables to the ANOVA models did not influence the statistical significance of hand placement, foot placement, or gender effects (i.e., Hand placement and foot placement remained significant during ascent and hand placement remained significant during descent. Gender was insignificant in all models consistent with Analysis 2).

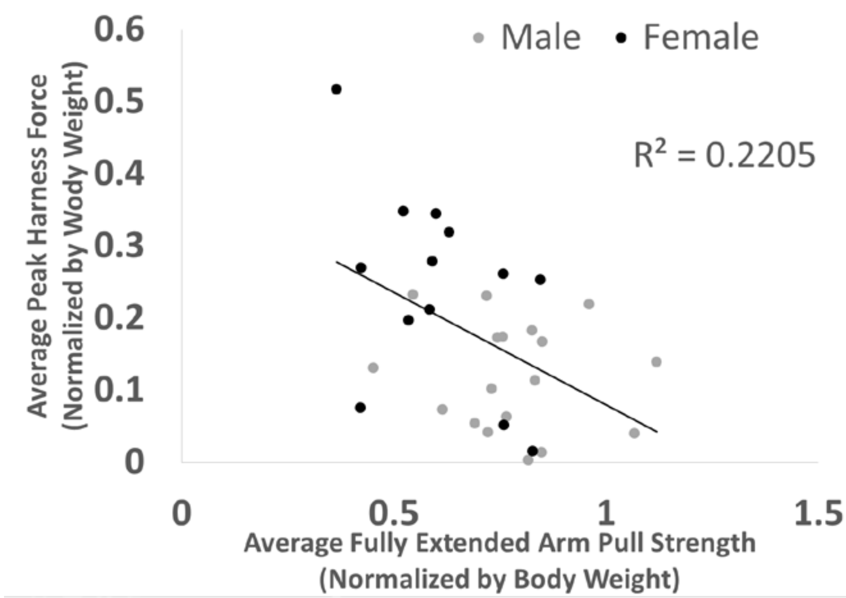


Figure 17: This plot shows the fully extended arm pull strength averaged across hands and glove condition for each subject plotted against the peak harness force during ascent averaged across glove condition for each subject. The line is the correlation.

G.3.3. Discussion

Personal, occupational and recovery responses were determined to affect the fall severity after a simulated misstep from a ladder. Specifically, gender and hand strength were important personal factors. Female participants had more severe falls than male participants and increased hand strength was associated with reduced fall risk. 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 hand and foot placements had an impact on fall severity. Specifically, participants who moved their hand one rung up had the most severe falls during ascent whereas participants who continue two rungs down had the highest fall severities during descent. Feet responses also affected fall severity during ascent 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.

Certain hand strength variables were associated with fall severity. Three (pull strength-full height, pull-strength-medium height and Jamar) of the five hand strength measures were significant during ascent and none were significant during descent. Increasing pull strength at a fully extended arm position had the strongest association with reduced harness forces. This suggests that interventions that improve hand strength (i.e., grasping rungs instead of rails and optimizing rung shapes) [23, 24, 44, 57] may be successful at reducing falls from ladders. Interestingly, strength as measured using break-away strength did not predict recovery. Break-away strength has been utilized in most previous studies to identify optimal rung designs and orientations for preventing falls [24, 57]. Our study suggests that measuring pull strength when the arm is fully extended may be more relevant to falling. Thus, these studies may need to be redone using a more relevant protocol. Also, our study found that increasing friction provided some marginal improvements in hand strength but did not influence recovery. The effects of friction on strength may have been too subtle to have a significant effect. Lastly, hand strength was not found to be as significant as hand position or foot positioning, which may indicate that strategies to optimize the speed of response should be pursued ahead of strategies that increase strength. Thus, while certain hand strength was found to contribute to recovery, its role was not as strong as expected.

Female participants were found to have more severe falls from ladder perturbations than male participants. These effects did not persist when including hand placement, foot placement and strength into the model during ascent or when including hand placement into the model during descent. This indicates that the increased fall severity associated with female subjects can be explained by their reduced strength and the fact that they utilized beneficial hand and foot placements after slipping. Differences in upper body strength across genders have been previously documented [59]. Females were more likely to utilize the hand placement and foot placement strategies with the most severe fall outcomes (HP1 and FP0 during ascent and HP2 during descent). Differences in anthropometry across genders may explain the greater propensity of female subjects to use non-preferred hand and foot placements. Establishing feet on a different rung while placing the hands higher (HP2 during ascent, HP0 during descent) requires additional height and may have put female subjects (who tend to be shorter) at a disadvantage for recovering from the perturbation since female subjects in this study were 150 mm shorter on average than the male subjects. Furthermore, female subjects had less hand strength than the male subjects (Figure 17). One way to narrow the recovery gap between female and male subjects may be to reduce rung diameters since females typically have smaller optimal grip spans than male subjects [60]. Early biomechanics studies that have explored ladder design utilized primarily male populations [19], which may have prevented ladders from being designed properly for female climbers. Thus, future research may want to consider ladder design adjustments that better account for differences in anthropometry and strength across the genders.

Table 6: Percentages of hand and foot responses utilized after a ladder perturbation by gender and climbing direction.

		HP2	HP1	HP0	HPN	FP2	FP1	FP0
Ascent	Males	37%	4%	20%	39%	26%	43%	30%
	Females	24%	18%	6%	53%	12%	50%	38%
Descent	Males	66%	20%	11%	3%	22%	47%	31%
	Females	73%	14%	9%	5%	10%	62%	29%

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 [61]. 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 [62].

Fall severity ladder falls can be decreased by improving hand placements. Lower harness forces associated with grasping a higher rung during ascent (HP2 improved recovery relative to HP1) and reestablishing grip on a higher rung during descent (HP0 improved recovery relative to HP2) may be explained from the increased strength associated with an extended arm posture [55]. Furthermore, larger hand movement times were associated with the hand placements that had the greatest fall severities (HP1 during ascent and HP2 during descent) (Figure 14). Strategies that reduce hand movement time and allow climbers to grasp a higher rung may improve recovery from ladder perturbations. One strategy that might improve response is to space the rungs closer together since movement time is negatively correlated with movement distance [63] and would make it easier to grasp for a higher rung.

Another strategy for enhancing recoveries from falls is to improve foot placement during ascent. Reestablishing a foot back on to a rung reduced fall severity from a ladder perturbation during ascent. One strategy might be to place the feet more anterior on the rungs since contacting the rungs with the forefoot has been shown to increase the risk that the foot will slip off of the rung [2]. Most previous studies on reducing ladder falls have focused on improving the interaction between the hands and the rungs [23, 24, 44, 57]. The results of this study suggest that additional research is needed to understand how to improve interaction between the foot and the rungs.

Glove condition did not affect fall severity. Although previous research believed increased force from high friction gloves would reduce ladder fall severity [44, 57], this study did not find a significant 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.

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I.Publications

I.1. Peer-Reviewer Publications

1. Schnorenberg, A.J., Campbell-Kyureghyan, N.H., **Beschorner, K.E.**, Biomechanical Response to Ladder Slipping Events: Effects of Hand Placement, *Journal of Biomechanics* 48 (14), 3810-3815. This manuscript described biomechanical response to ladder slipping events including EMG activity and the timing of different post-slip responses (Aim 1).
2. Pliner, E.M., Campbell-Kyureghyan, N., **Beschorner, K.E.**, 2014, Effects of foot placement, hand positioning, age and climbing biodynamics on ladder slip outcomes, *Ergonomics* **57(**11), pp. 1739-1749.
This manuscript described the effects of various risk factors for ladder slips (foot placement, hand positioning and age) and described differences in climbing styles between subjects who experienced a slip and those who did not experience a slip. (Aim 1)

I.2. Proceedings

1. E.M. Pliner, N.J. Seo, K.E. Beschorner, 2015, Climbing Direction, Number Of Contact Points And Gender Influence Recovery From Ladder Falls But Not Glove Use, **American Society of Biomechanics**, Columbus, OH. This proceedings paper identified the impacts of different risk factors on recovery from slipping (Aim 2).
2. E.M. Pliner, N.J. Seo, K.E. Beschorner, 2015, Hand And Foot Responses That Improve Ladder Fall Recovery, **American Society of Biomechanics**, Columbus, OH. This proceedings paper characterized the response to ladder missteps (Aim 1) and determined the impact of these responses on recovery (Aim 2).
3. Salehi, S.H., Slota, G.P., Beschorner, K.E., Seo, N.J., 2014, Effects of Upper Limb Posture and Hand-Rung Friction Condition on a Person's Pull Strength Related to Preventing Falling from a Fixed Ladder, **World Congress of Biomechanics**, Boston, MA. This proceedings paper characterized the impacts of gloves, posture and testing method on hand strength (Aim 2).
4. E. Pliner, K. Beschorner, N. Campbell-Kyureghyan, 2013, Effects of Foot Placement on Ladder Slip Outcomes, **American Society of Biomechanics**, Omaha, NE. This proceedings paper characterized the effects of foot placement and climbing biomechanics on slip risk (Aim 1).
5. A. Paul, Marissa Lovell, N. Campbell-Kyureghyan, K. Beschorner, 2013, Biomechanical response to ladder slipping events: Effects of Hand Placement on Response and Recovery. **American Society of Biomechanics**, Omaha, NE. This proceedings paper characterized the recovery response to ladder slips (Aim 1).

I.3. Thesis:

Pliner, E.M. [2015] Individual, Occupational and Biomechanical Factors that Affect Slip and Fall Risk from Fixed Ladders, M.S. Thesis, University of Wisconsin-Milwaukee. This thesis described biomechanical differences between subjects who slipped and those who did not slip (Aim 1) and described the effects of different risk factors on recovery after a simulated misstep (Aim 2).

J.Inclusion Enrollment Table

Program Director/Principal Investigator (Last, First, Middle): Rahman, Mohammad

Inclusion Enrollment Report

This report format should NOT be used for data collection from study participants.

Study Title: Quantifying the Recovery Response and Role of Hand Strength During Ladder Falls

Total Enrollment: 40 **Protocol Number:** 11.366

Grant Number: NIOSH R21OH010038

PART A. TOTAL ENROLLMENT REPORT: Number of Subjects Enrolled to Date (Cumulative) by Ethnicity and Race					
Ethnic Category	**Females**	**Males**	**Sex/Gender Unknown or Not Reported**	**Total**	
Hispanic or Latino	0	2	0	2	**
Not Hispanic or Latino	14	23	0	37	
Unknown (individuals not reporting ethnicity)	1	0	0	1	
Ethnic Category: Total of All Subjects*	15	25	0	40	*
Racial Categories					
American Indian/Alaska Native	0	0	0	0	
Asian	3	2	0	5	
Native Hawaiian or Other Pacific Islander	0	0	0	0	
Black or African American	0	0	0	0	
White	12	19	0	31	
More Than One Race	0	4	0	4	
Unknown or Not Reported	0	0	0	0	
Racial Categories: Total of All Subjects*	15	25	0	40	*

PART B. HISPANIC ENROLLMENT REPORT: Number of Hispanics or Latinos Enrolled to Date (Cumulative)					
Racial Categories	**Females**	**Males**	**Sex/Gender Unknown or Not Reported**	**Total**	
American Indian or Alaska Native	0	0	0	0	
Asian	0	0	0	0	
Native Hawaiian or Other Pacific Islander	0	0	0	0	
Black or African American	0	0	0	0	
White	0	0	0	0	
More Than One Race	0	2	0	2	
Unknown or Not Reported	0	0	0	0	
Racial Categories: Total of Hispanics or Latinos**	0	2	0	2	**

* These totals must agree.
** These totals must agree.

K.Inclusion of Children

Children under 21 years of age were eligible and participated in this study.

L.Materials Available for Other Investigators

None.

EQUIPMENT INVENTORY LIST AUTHORIZATION/PURCHASE

Report Date: 10/19/2015
Project Title: Quantifying the Recovery Response & Role of Hand Strength During Ladder Falls
Grantee Name: Univ of Wisconsin-Milwaukee
Grants Management Officer: Mary Pat Shanahan

Grant Number: 5R21OH010038
Project Period: 9/1/2012 to 8/31/2015

Project Officer: Linda J Frederick
Grants Specialist: Brandis Belser

Description of Item (i.e., pH Meter)	Mfr.[1] (i.e., Fischer)	Serial Number	Quantity	Condition	Location	Purchase Cost	Date Received
None	Click here to enter text.	Click here to enter text.	Click here to enter text.	Choose an item.	Click here to enter text.	$Click here to enter text.	Click here to enter a date.

[1]Mfr. (Manufacturer)

Property Administrator & PO Disposition Recommendation and Instructions:

Description of Item (copy from above)	Disposition	Address[1]
None	Choose an item.	Attn: Brandis Belser Centers for Disease Control & Prevention Peachtree Distribution Center 3719 North Peachtree Road, #100 Chamblee, GA 30341
Click here to enter text.	Choose an item. Click here to enter text.	
Click here to enter text.	Choose an item. Click here to enter text.	
Click here to enter text.	Choose an item.	

1The CDC Warehouse is the central receiving point for the delivery of all non-hazardous and non-perishable supplies and equipment, CDC – AM – 2004-03, update 2010

Form Approved Through 06/30/2012
OMB No. 0925-0001

Department of Health and Human Services

Final Invention Statement and Certification

(For Grant or Award)

DHHS Grant or Award No.

R21OH010038

A. We hereby certify that, to the best of our knowledge and belief, all inventions are listed below which were conceived and/or first actually reduced to practice during the course of work under the above-referenced DHHS grant or award for the period

9-1-2012 through 8-31-2015 .

original effective date — *date of termination*

B. Inventions (Note: If no inventions have been made under the grant or award, insert the word *"NONE"* under Title below.)

NAME OF INVENTOR	TITLE OF INVENTION	DATE REPORTED TO DHHS
	NONE	
(Use continuation sheet if necessary)		

C. Signature — This block ***must*** be signed by an official authorized to sign on behalf of the institution.

Title
Associate Director

Typed Name
Ronald Fleischmann

Signature
[signature]

Date
10/19/15

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HHS 568 (Rev. 06/09)