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# Factors affecting fall severity from a ladder: impact of climbing direction, gloves, gender and adaptation

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## Abstract

Ladder falls cause many fatal injuries. The factors that affect whether a ladder perturbation leads to a fall are not well understood. This study quantified the effects of several factors on a person's ability to recover from a ladder perturbation. Thirty-five participants each experienced six unexpected ladder missteps, for three glove conditions (bare hands, high friction, low friction) and two climbing directions (ascent, descent). Fall severity was increased during ladder descent ($p < 0.001$). Gloves did not affect fall severity. Females compared to males had greater fall severity during ascent ($p < 0.001$) and descent ($p = 0.018$). During ascent, females had greater fall severity during the second perturbation but similar fall severity to males during the other perturbations. Additional protection may be needed when descending a ladder. Also, females may benefit from targeted interventions like training. This study does not suggest that gloves are effective for preventing ladder falls

### Keywords

ladder falls; climbing direction; gender

## 1. Introduction

Ladder falls are the leading cause of fatal falls (BLS 2012) and 63 percent of ladder injuries result in a fracture or sprain (Partridge, Virk et al. 1998). Nearly half of these ladder fall fractures lead to over $5,000 in medical cost per case (Smith, Timmons et al. 2006). However, these severe injuries are believed to be preventable through safer ladder climbing practices (Muir and Kanwar 1993, Socias, Chaumont Menéndez et al. 2014). Identifying the climbing practices associated with reduced fall risk and the individuals at risk for falling is important to develop and target strategies for reducing the number of people who suffer from injuries of ladder falls.

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Ladder falls can be broadly categorized into falls from ladders and falls with ladders (Shepherd, Kahler et al. 2006). A fall with a ladder is typically a result of unstable ladder placement (Shepherd, Kahler et al. 2006, Smith, Timmons et al. 2006, Hsiao, Simeonov et al. 2008). Instability in the ladder placement can cause the ladder to tip or the base to slide. Therefore, prevention strategies for falls with ladders have focused primarily on securing the ladder (Hsiao, Simeonov et al. 2008), improving friction between the ladder base and ground surface (Chang, Chang et al. 2005) or optimizing the inclination angle of extension ladders (Chang, Chang et al. 2004). A fall from a ladder is the result of the climber losing their supporting hand and/or foot contact with the ladder (e.g. slip of the hand or foot). A majority of falls from ladders result from a climber's overbalance, slip, or misstep (Shepherd, Kahler et al. 2006). The ladder design and biomechanics of ladder climbing have been found to be associated with slip propensity and a climber's ability to recover from a slip (Pliner, Campbell-Kyureghyan et al. 2014, Schnorenberg, Campbell-Kyureghyan et al. 2015). The present study aims to expand on this research to identify factors that affect a person's ability to recover after a ladder climbing perturbation.

Epidemiology research has suggested that climbing direction (ascent/descent) may be an important risk factor for falls from ladders. A review of mining injury reports revealed that ladder fall injuries occur three times more often for miners exiting (and thus descending ladders) mining equipment compared with entering equipment (Moore, Porter et al. 2009). One explanation that was offered by the authors of this study is that miners may have poorer balance during descent due to the amount of vibration exposure that is experienced between ascent at the start of a shift and descent at the end of the shift (Moore, Porter et al. 2009). However, previous research has suggested that exposure to vibration does not have substantial short-term impacts on balance (Cornelius, Redfern et al. 1994, Santos, Larivière et al. 2008). An alternative hypothesis is that more falls are experienced during ladder descent because recovering from a perturbation during descent is more challenging than ascent due to the body's downward momentum. Although injury records show more descending ladder falls than ascending, a gap in the literature exists regarding whether this is because of some exposure that typically occurs between ascent and descent or because recovering from a perturbation during descent is more challenging.

Glove use has also been suggested to be an important risk factor for recovery after a climbing perturbation since glove use affects friction and tactile perception. The use of gloves is known to impact the achievable forces between a hand and a handle, which is believed to affect a person's ability to recover from a ladder climbing perturbation (Barnett and Poczynck 2000, Hur, Motawar et al. 2012, Hur, Motawar et al. 2014). Specifically, the coefficient of friction (COF) between the rung and hand is positively correlated with the amount of frictional force that can be applied to a rung before the rung is pulled out of the hand's grasp (Hur, Motawar et al. 2012). Also, a low COF between the glove and rung has been associated with an increase in the muscular effort required to stabilize a sudden upward impulse force applied to a rung (Hur, Motawar et al. 2014). However, previous studies that examined the impact of friction on recovery from a ladder perturbation only considered the interaction between the hand and the rung in a stationary position (Barnett and Poczynck 2000, Hur, Motawar et al. 2012, Hur, Motawar et al. 2014) without consideration of the role that the rest of the body plays after a ladder perturbation. This method may be an oversimplification of the effects that gloves have between the hand and rung during an actual ladder falling scenario. Thus, additional research is needed to determine if these changes in force application translate into improved ability to recover from a ladder perturbation.

Contradicting evidence exists regarding if gender would have an impact on ladder fall severity. Differences across genders in anthropometry and strength may lead to different capacities for reaching rungs and applying the required forces, which could then have an impact on fall severity. Females have less upper body strength than males (Miller, MacDougall et al. 1993) even after normalizing for body mass (Young, Woolley et al. 2009) and increased upper body strength is believed to be critical to prevent a ladder fall (Hur, Motawar et al. 2012). Also, females are shorter in stature, have shorter arms and tend to have smaller hand sizes (Chaffin, Andersson et al. 1999), which may impact their ability to reach and grasp ladder rungs. Previous research found females to have a lower grip force than males, which is partially due to their smaller hand size (Fransson and Winkel 1991, Seo and Armstrong 2008). Yet, male workers account for the majority of ladder fall injuries, have higher ladder fall incidence rates (Socias, Chaumont Menéndez et al. 2014), and incur more severe ladder fall injuries than female workers (Björnstig and Johnsson 1992). These epidemiology studies should be interpreted cautiously since they may be affected by gender differences in the frequency of using ladders during work. Thus, controlled laboratory studies may provide better characterization of the effects of gender on ladder falling risk.

Repeated perturbations to a ladder climber have not been studied to quantify the adaptation process. In gait perturbation studies, participants have been found to alter their gait biomechanics when perturbed repeatedly (i.e. by shifting their center of mass anteriorly, reducing foot angle, increasing knee angle, and decreasing trunk angle) (Owings, Pavol et al. 2001, Bhatt, Wening et al. 2006). These adaptations can be made before or after perturbation onset (Bhatt, Wening et al. 2006), and are correlated with increased stability (Bhatt, Wening et al. 2006) and potential fall elimination (Owings, Pavol et al. 2001). In addition, adaptation changes have also been noticed in participants anticipating a slip during gait (Cham and Redfern 2002). Similarly, a person’s ability to recover from a perturbation and avoid a fall may change after repeated exposures to a ladder perturbation.

The purpose of this study is to determine the impacts of climbing direction, gloves, gender and adaptation on fall severity following a ladder perturbation. This study will test the following hypotheses. Hypothesis 1: Falls during ladder descent will result in more severe fall outcomes compared to ladder ascent. Hypothesis 2: The use of gloves will affect fall severity outcomes. Hypothesis 3: Female ladder climbers will have more severe fall outcomes following a perturbation than their male counterparts. Hypothesis 4: Fall severity will vary with continuing perturbations.

## 2. Material & Methods

### 2.1 Subjects

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

### 2.2 Apparatus

A vertical 12-foot custom-designed ladder was secured in the middle of the motion capture volume (Figure 1). The ladder had twelve cylindrical rungs, which were 31.8 mm (1.25 in) in diameter and spaced 305 mm (12 in) apart, in compliance with U.S. Occupational Safety and Health Administration (OSHA) standards (OSHA 2003). All rungs excluding the fourth rung were equipped with two strain gauges that were sampled at a frequency of 2000 Hz. The strain gauges were located at the bottom and the side of the rung facing the climber, positioned in the center. To ensure all participants experienced the same climbing perturbation, a ladder misstep was created by a mechanical release, based-off a specific event in the individual's climbing cycle. A simulated misstep perturbation was induced on the fourth rung (referred to as the breakaway rung hereafter) by releasing the rung under the foot during climbing. The left and right side of the breakaway rung had a spring-loaded connector inside the rung. A rod was used to compress each spring-loaded connection to attach the breakaway rung with the ladder. The rod and spring connection was held in place with electric magnets during baseline climbing. When the breakaway rung was triggered to release, the magnets would demagnetize and the springs would extend, breaking the rungs connection with the ladder. The breakaway rung was programmed to release when less than five percent of the participant's body weight remained on the previous rung. Foot-off of the leg contralateral to the perturbation leg was selected as the perturbation time, based on previous research that found that this is typically the time when the foot slips off of a rung (Schnorenberg, Campbell-Kyureghyan et al. 2015). Prior to testing, participants were informed they would be climbing stable and unstable ladders, but they were not informed of the perturbation mechanism and location.

### 2.3 Experimental Approach

The testing session was started by recording the mass and height of the participant. The participant was equipped with climbing attire, footwear, shin guards and a safety harness. The footwear was a standard work shoe with a rubber sole and raised heel. The shin guards acted as additional protection to the climber in case their legs 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) and posterior superior iliac spine (PSIS) torso markers were analyzed in this study. Markers were recorded by 13 motion capture cameras at a frequency of 100 Hz (Motion Analysis Raptor Corp., Santa Rosa, CA). In a single testing session, participants were perturbed three times while ascending and three times while descending the ladder out of 30 total ascent and descent trials. The perturbations were conducted once in each climbing direction (ascent and descent) for each of three different glove conditions (bare hands, latex-coated gloves and cotton gloves). The latex-coated gloves was selected as a high friction glove condition whereas the cotton gloves were selected as a low friction glove condition (Hur, Motawar et al. 2012). Both gloves were bought off-the-shelf. High friction gloves were made of knitted fabric with a latex palm (HD30503/L3P, West Chester, Inc., Monroe, OH) and low friction gloves were made of 100% cotton (COTPR, Drillcomp, Inc., New Hope, PA). The high friction gloves were 1.57 mm thick and the low friction gloves were 0.31 mm thick. Three glove sizes were available for the high friction and low friction gloves to accommodate different hand sizes. Perturbation order was randomized. Participants acclimated to the ladder with each glove condition prior to data collection. Three to six regular climbing trials were collected prior to each perturbation to reduce anticipation of the perturbation (Pliner, Campbell-Kyureghyan et al. 2014). Rest time of approximately two minutes was allotted after each perturbation. Participants were instructed to climb at a “comfortable but urgent pace” to simulate climbing speed of a regular-to-busy workday. To ensure participant safety, each participant had an impact mat at the bottom of the ladder, a spotter and belayer.

### 2.4 Data and Statistical Analysis

Fall severity to a ladder perturbation was measured by the load cell that was attached to the safety harness. A high harness force was associated with a more severe fall and a low harness force was associated with a less severe fall (Yang and Pai 2011). The harness force was normalized to each participant’s body weight. Therefore, fall severity was analyzed as a continuous variable and defined as the peak harness force found across a period of time that represented the time from perturbation onset (start of fall) until the time when the person had either fallen into the harness or had arrested the fall (end of fall). The velocity of climber’s mid-hip joint center was also quantified at the time of perturbation onset and the peak downward velocity between the start of fall and end of fall in order to characterize the momentum of the body. These measures were intended to explain differences in the body’s momentum between ascent and descent. A more downward (negative) mid-hip joint center velocity was indicative of greater fall severity (Pavol and Pai 2002, Pai 2003, Beschorner and Cham 2008). The start of fall was defined as the time that the breakaway rung was triggered to release. The end of fall was defined as the first local maximum in harness force after the first minimum of mid-hip joint center’s downward vertical displacement. This method was selected based on initial observations in the harness force data where the peak harness force was typically observed either just before or shortly after the local minimum in hip elevation. Mid-hip joint centers were calculated using Bell’s Method and the ASIS and PSIS markers (Bell, Pedersen et al. 1990). Trials were excluded (43 out of 210 trials) due to technical equipment error (27 trials), participant withdrawal (8 trials), and incongruence between the end of fall time calculated by the algorithm versus the time identified by visual inspection (8 trials).

Two statistical analyses were used to determine the effect of climbing direction (first analysis) and the other independent variables (second analysis) on fall severity. A repeated measures ANOVA was performed with normalized harness force as the dependent variable; while subject number (random), perturbation number (nominal) and climbing direction were the independent variables. Perturbation number was added to the model to adjust for potential confounding effects due to participants adapting to the multiple perturbations. Gloves and gender were not included in the first model because ladder ascent and descent were determined to be fundamentally different tasks and, therefore, it was determined that the effects of gloves, gender and adaptation should be assessed for ascent and descent separately. To assess the body's momentum between climbing direction, repeated measures ANOVAs were performed with the mid-hip joint center velocity at perturbation onset and peak downward velocity as the dependent variables. In consistency with the first ANOVA, subject number (random), perturbation number (nominal) and climbing direction were the independent variables. The second analysis was a generalized linear model with normalized harness force as the dependent variable and subject number (random), perturbation number (nominal), glove condition, gender, and first order interactions as the independent variables. Models were performed separately for ascent and descent. In addition, first order interactions that did not occur for every condition were removed (e.g., subject number x gender). A square root transformation was needed to ensure that harness force was normally distributed for both analyses. A significance level of 0.05 was used. Post-hoc comparisons were made using Tukey HSD tests for any primary effects with more than two categories. Given the large number of combinations for the interaction effects between gender and perturbation number (12 combinations for gender x perturbation number), t-tests using a Bonferroni correction (0.05/6) were performed that only considered differences across gender for each perturbation number (i.e., differences between male and female for perturbation 1, 2, 3, etc.). This limited post-hoc test reduced the number of comparisons from 12 to 6 in order to provide sufficient power for describing this interaction. An additional analysis was performed on climbing cycle time to assess anticipation of the perturbation. This temporal parameter is similar to another study that identified changes in stance duration during slip-anticipation gait trials (Cham and Redfern 2002). Cycle time was calculated from the baseline trial prior to each perturbation trial. Cycle time was defined as the time period from foot contact on the third rung to foot contact on the fifth rung for ascending perturbations and vice versa for descending perturbations. Foot contact was determined from strain gauge data on the rungs captured in the vertical direction and filtered using a zero-phase fourth-order Butterworth low-pass filter with a cut-off frequency of 36 Hz (Chang, Chang et al. 2011). Foot contact was defined as the point in time when strain activity exceeded 10% of the peak strain activity on the corresponding rung during the baseline trial. A repeated measures ANOVA was run with cycle time as the dependent variable and subject number (random) and perturbation number (nominal) as the dependent variables. Analyses were run separate by climbing direction.

## 3. Results

Climbing direction was found to have a substantial impact on fall severity. The average normalized harness force (standard deviation) observed in this study across all trials was 0.288 (0.258). Descending perturbations led to harness forces more than double those of ascending perturbations, which confirmed Hypothesis 1 ($p < 0.001$, $F = 65.325$) (Figure 2). Harness force did not significantly change across the six perturbations ($p = 0.078$, $F = 2.033$) in the ANOVA

The mid-hip joint center velocities were higher for ascent than decent at perturbation onset ($p < 0.001$; $F = 1090.380$). In addition, ascending perturbations had a smaller (less negative) peak downward mid-hip joint center velocity than descending perturbations ($p < 0.001$; $F = 280.174$) (Figure 3). The mid-hip joint center velocity did not significantly change with perturbation number at perturbation onset ($p = 0.437$; $F = 0.986$), but slightly reduced (less negative) at peak downward velocity from the first to sixth perturbation ($p = 0.032$; $F = 2.533$). The average (standard deviation) mid-hip joint center velocity for ascending and descending climbers was 0.709 (0.180) m/s and −0.015 (0.153) m/s at perturbation onset, respectively. The average (standard deviation) minimum mid-hip joint center velocity was −0.869 (0.259) m/s and −1.504 (0.351) m/s for ascending and descend perturbations, respectively.

Gender and the interaction between gender and perturbation order but not glove condition were determined to affect fall severity. Harness force did not significantly vary across glove condition during ascent or descent (Table 1). Thus, Hypothesis 2 was not confirmed. Average normalized harness force for bare hands, high friction gloves, and low friction gloves was 0.171 (0.154), 0.178 (0.174), and 0.194 (0.184) during ascent and 0.393 (0.261), 0.369 (0.302), and 0.453 (0.302) during descent, respectively. Females had significantly higher normalized harness forces than males during ascent and descent (Table 1), confirming Hypothesis 3. Specifically, normalized harness forces were 0.13 (0.14) and 0.26 (0.18) for males and females on ascent and 0.34 (0.24) and 0.50 (0.33) for males and females on descent, respectively. Perturbation order did not influence the overall harness forces for either ascent or descent, thus not confirming Hypothesis 4 (Table 1). However, the gender x perturbation number interaction was significant during ascending perturbations (Table 1). Females had a greater fall severity on their second perturbation during ascent compared to male participants (Figure 4.a). The gender x perturbation number interaction during descent was not significant ($p = 0.087$, Figure 4.b). The gender x glove condition and perturbation number x glove condition interactions were not significant for either ascent or descent (Table 1). In the analysis to assess anticipation, climbing cycle time was not significant across perturbation number for both ascending ($p = 0.807$; $F = 0.455$) and descending ($p = 0.119$; $F = 1.865$) climbing directions.

## 4. Discussion

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

This study confirms that ladder descent leads to more severe falls than ladder ascent. Given that a previous study defined a harness weight support threshold for falling to be 30% of body weight (Yang and Pai 2011), the high harness forces for descending perturbations (40% of body weight) indicate that relatively severe falls were observed during descent. The average harness forces during ascent (18% of body weight) were well under this 30% threshold, suggesting that fall severity during ascent was relatively mild. This study suggests the reason that more descending falls have been reported epidemiologically (Moore, Porter et al. 2009) is because ladder descent is a more hazardous task than ladder ascent. Lower fall severity during ascent may be due to the time delay between perturbation onset and when the climber begins to a have downward acceleration. At perturbation onset, the body was confirmed to be moving upward during ascending and downward during descending perturbations (Figure 3). Thus, the body was already accelerating (as opposed to decelerating) downward at perturbation onset during descending perturbations. This led to a smaller peak downward vertical velocity for ascent, indicating a less severe fall for ascending perturbations than descending (Pavol and Pai 2002, Pai 2003, Beschorner and Cham 2008). Therefore, the momentum of the body after a perturbation during ladder descent may be too large to recover without assistance from the harness during ladder descent. Increased risk during ladder descent may explain why another study found that participants descended a ladder slower than when ascending a ladder (Hammer and Schmalz 1992). Also, the act of placing the feet further from the head may reduce the visual information that is available to guide foot placement during descent. Regardless of the mechanism, this study suggests that targeting interventions such as fall arrest systems (e.g., climbing harness with a safety locking sleeve) (Vi 2008) to ladder descent may be effective at preventing ladder fall injuries.

Glove condition did not affect fall severity. Although previous research indicated that increased force from high friction gloves would reduce ladder fall severity (Hur, Motawar et al. 2012, Hur, Motawar et al. 2014), this study did not confirm this effect. One explanation is that the safety harness supported enough of the body weight such that the hand forces did not become great enough to force a decoupling of the hand from the rung. Another explanation is that hand force may not be a limiting factor in fall recovery. Previous research has found that even in low friction handholds, participants were capable of generating forces between 73% and 88% of their body weight for each hand (Young, Woolley et al. 2009). Additional research that allows the climber to fall a greater distance before engaging the harness may lead to hand-rung decoupling where gloves play a more important role. Overall, this study suggests that increased force from high friction gloves does not translate to reducing fall severity at least during the portion of a fall leading up to the time of harness support.

Females had greater difficulty recovering from a ladder fall than males. Interestingly, fall severity initially increased for females during ascent whereas fall severity for males did not change with continuing perturbations (Figures 4.a). This result is in contrast to many fall-related perturbation studies, where fall outcome was found to decrease with continuing perturbations (Bhatt, Wening et al. 2006, Pai and Bhatt 2007). A key difference in this study as opposed to other fall-related studies is that a misstep from a ladder may be a more novel experience than a perturbation experienced during gait. Most individuals have experienced a slip or trip during walking with daily-living, resulting in some form of preset response from the central nervous system (Bhatt, Wening et al. 2006) whereas a ladder misstep may be a completely new experience. Therefore, a different motor adaptation process may be used to develop effective responses to ladder perturbations. Previous research studies on motor skill development have divided the motor learning process into three phases: exploration, discovery and stabilization, and exploitation (Araujo, Davids et al. 2009). A solution is discovered after an individual has explored many degrees of freedom to find movements most relevant to achieve the desired outcome (Araujo, Davids et al. 2009). This exploration leads to unpredictable outcomes which can be worse than the outcome during the first attempt (Newell, Liu et al. 2001). Females may have utilized the exploration phase of decision making more than males, resulting in an increase in their fall severity before a decrease. Importantly, females decreased their fall severity after the second perturbation suggesting that they identified a successful recovery response or abandoned exploration and returned to their initial response. Gender differences such as upper body strength (Muir and Kanwar 1993) and anthropometry (Chaffin, Andersson et al. 1999) may explain why this effect was only seen in females and not males. For example, reduced strength and stature in female participants may have forced them to fine-tune their strategy as opposed to relying on their strength and height. Male participants were taller than females on average ($p < 0.001$) which may have allowed male participants to reach higher for rungs or extend lower to reestablish foot placement onto the rungs after a misstep.

This research provides important information regarding fall severity factors during ladder climbing that may provide a foundation for future research that investigates interventions and further explores the mechanisms for the observed gender effects. For example, future research may aim to develop interventions that focus on reducing the severity of ladder falls during descent. Also, research that controls for strength and anthropometry may help determine if the gender effects are due to strength and anthropometry differences or due to some other difference. Lastly, training programs that allow female ladder climbers to experience ladder perturbations and go through the exploratory motor learning phase in a safe and controlled environment may lead to safer responses to actual ladder perturbations. Previous research has demonstrated that a perturbation in training can be translated across contexts (Parijat and Lockhart 2012) and from a lab environment to a real living environment (Rosenblatt, Marone et al. 2013).

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

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

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**Highlights:**

- Ladder climbers were perturbed by releasing a rung under the foot while climbing.
- Harness forces were used to quantify fall severity after the perturbation.
- Fall severity was more severe for ladder descent compared with ascent.
- Females had greater fall severity than males.
- High friction and low friction gloves did not influence fall severity.

**Figure 1:**
Instrumented ladder with electronically-controlled breakaway rung. The ellipse encircles the breakaway rung.

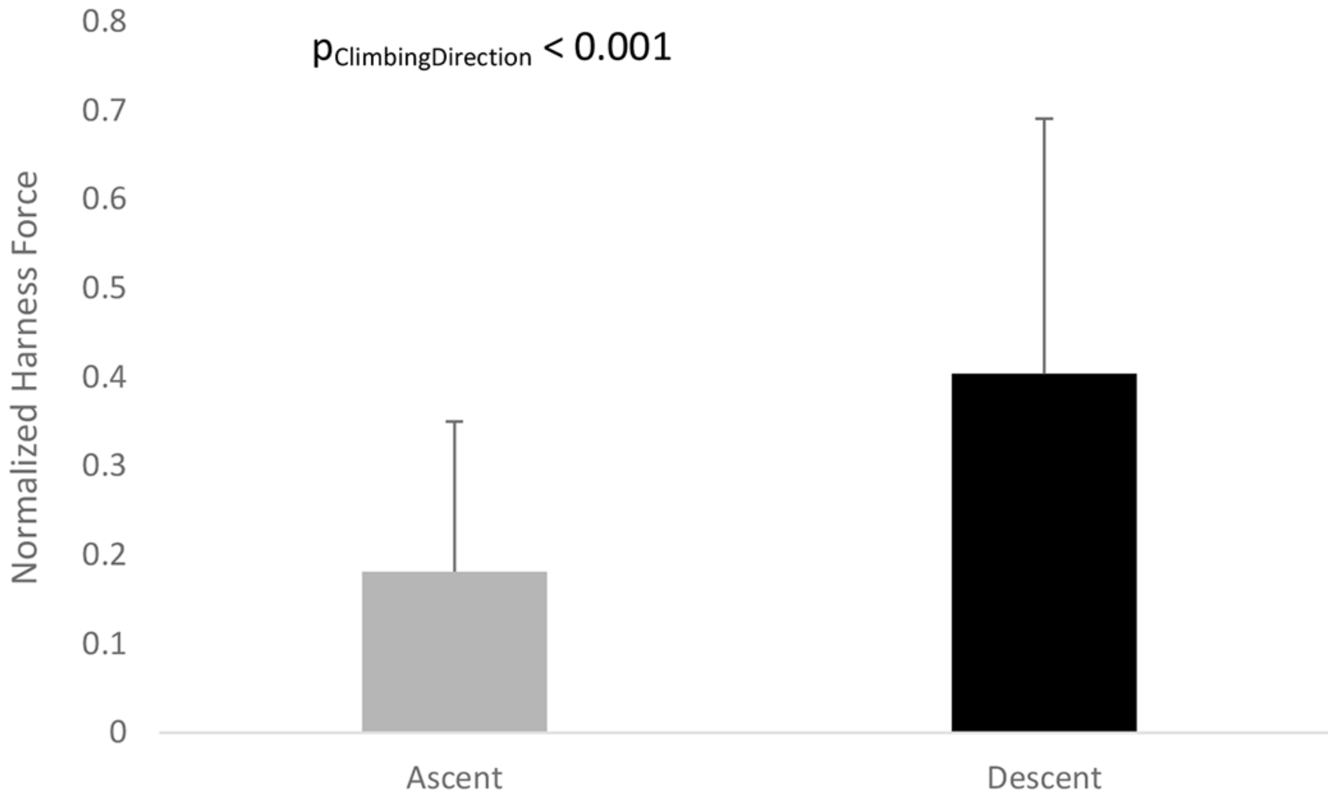


**Figure 2:**
Average harness force normalized to body weight for ascent and descent. Error bars represent standard deviation.

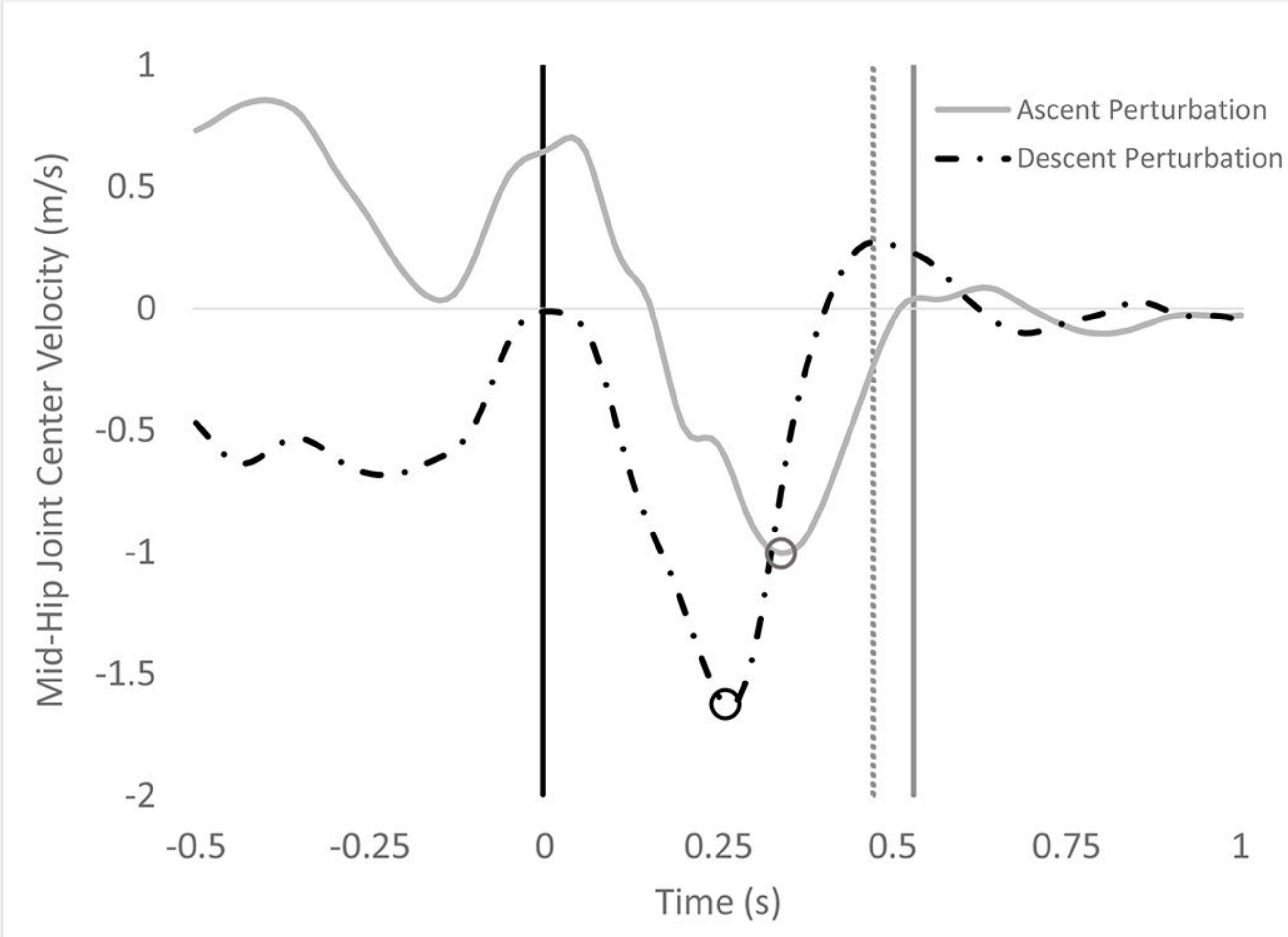


**Figure 3:**
Representative velocity of a climber's vertical mid-hip joint center from the time of perturbation onset (vertical black line, time = 0) during an ascending (solid gray line) and descending (black dashed line) perturbation. The vertical gray lines show the time of end of fall for ascent (solid) and descent (dotted) perturbations. The circles represent the peak downward velocity.

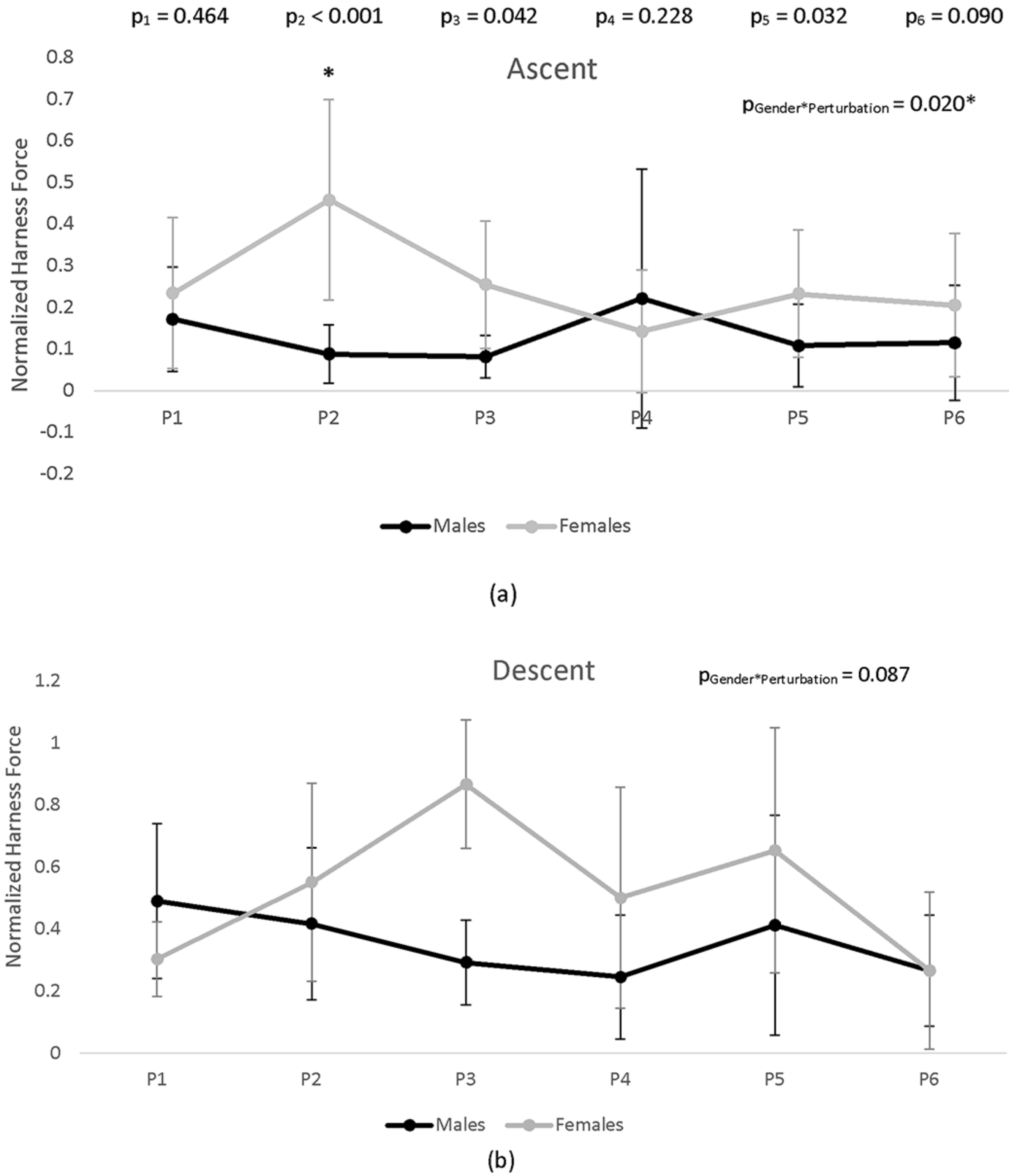
p₁ = 0.464
p₂ < 0.001
p₃ = 0.042
p₄ = 0.228
p₅ = 0.032
p₆ = 0.090
Ascent
*
pGender*Perturbation = 0.020*
Normalized Harness Force
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
P1
P2
P3
P4
P5
P6
Males
Females
(a)
Descent
pGender*Perturbation = 0.087
Normalized Harness Force
1.2
1
0.8
0.6
0.4
0.2
0
P1
P2
P3
P4
P5
P6
Males
Females
(b)

**Figure 4:**

Average harness force normalized to body weight for males (black lines and black markers) and females (gray lines and gray markers) for perturbations one (P1) through six (P6) during ascent (a) and descent (b). Error bars represent standard deviation.

## Table 1:

Statistical results of analysis 2: generalized linear model

**Ascent**

| | Gender | Perturbation Number | Glove Condition | Gender x Perturbation Number | Gender x Glove Condition | Perturbation Number x Glove Condition |
|---|---|---|---|---|---|---|
| p-value | < 0.001* | 0.484 | 0.461 | 0.020* | 0.258 | 0.135 |
| Chi-Sq. | 13.254 | 4.472 | 1.549 | 13.391 | 2.708 | 14.913 |

**Descent**

| | Gender | Perturbation Number | Glove Condition | Gender x Perturbation Number | Gender x Glove Condition | Perturbation Number x Glove Condition |
|---|---|---|---|---|---|---|
| p-value | 0.018* | 0.065 | 0.447 | 0.087 | 0.140 | 0.190 |
| Chi-Sq. | 5.624 | 10.389 | 1.610 | 9.608 | 3.935 | 13.636 |