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Strategies to reduce fall severity after a perturbation during ladder climbing

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Technical Abstract

Background: Falls from ladders remain a significant cause of workplace injuries.

Purpose: Collective biomechanical responses associated with minimizing fall severity were investigated.

Methods: Secondary analysis. In a laboratory, a perturbation of a ladder rung (simulating a misstep) was applied during ladder climbing of healthy adults. Hand and foot placements after the perturbation were characterized by whether they would be anticipated to improve fall outcomes (based on a previous analysis). The number of beneficial fall recovery factors (i.e., high upper body strength, optimal hand placement, reestablished foot placement) on fall severity was assessed. Underlying temporal mechanisms of hand and foot placement response were further investigated.

Results: Participants recovered from a perturbation better if they achieved a greater number of beneficial fall recovery factors (e.g., optimal hand placement *and* reestablished foot placement vs. either alone). The optimal hand placement was achieved when the hand moved prior to the climbing perturbation toward the next rung (2 rungs up) during ascent, and when the hand regressed the original rung (did not move to the next rung) after the climbing perturbation during descent. These strategies were associated with faster hand-rung contact after the perturbation. Reestablished foot placement was more likely to occur when more time was allotted before foot-rung contact.

Conclusions: Combining fall recovery strategies of a higher hand hold for higher upper limb strength and reestablishing the foot with control may be strategies to maximize recovery from a fall from a ladder.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

ladder fall; biomechanics; hand; upper limb; strength; foot slip; perturbation

1. Introduction

Falls are the second leading cause of workplace fatalities, accounting for 16% of all workplace deaths and 38% of all construction fatalities (U.S. Department of Labor, 2022a). The majority (80.9%) of fall related fatalities are due to falls to a lower level (U.S. Department of Labor, 2022a). Approximately a quarter of those deaths involve ladders (U.S. Department of Labor, 2022b). Falls from a ladder occur not only in workplaces but also increasingly in residential settings (Jain et al., 2014; Mitra et al., 2007). Falls from a ladder in residential settings result in death or hospital admissions (Aldailami et al., 2022; Hamdard et al., 2023) with serious consequences (Schaffarczyk et al., 2020).

Falls from a ladder are often caused by decoupling between a worker and the ladder such as hand-ladder decoupling and foot-ladder decoupling (Partridge et al., 1998; Shepherd et al., 2006; Smith et al., 2006). Risk of foot slips exists, especially during the use of vertical ladders (Blowsick & Chaffin, 1990; Martin et al., 2020). A slip or misstep of a climber's foot has been reported in 19–28% of ladder fall cases (Cabilan et al., 2018; Cohen & Lin, 1991; Faergemann & Larsen, 2001; Shepherd et al., 2006). When the decoupling occurs, the worker must react and reestablish the hand and foot on the rung to arrest the fall (Barnett & Poczynok, 2000). Recent studies (using the same data set as the present study) have shown that when people experience a misstep, as simulated by a release of a ladder rung under a foot, the resulting fall severity was influenced by the upper limb strength, hand placement, and whether the foot reestablished contact on the ladder rung (Pliner et al., 2020; Pliner et al., 2019). While these previous studies provide insights on the factors affecting fall severity, the summative effect of these strategies and knowledge of underlying mechanisms to achieve these strategies are unknown (Table 1). This information could be useful in tuning climber training strategies and evaluating the impact of ladder design features on fall risk.

The objective of the current study was to investigate strategies associated with minimizing fall severity. Specifically, our secondary analysis of earlier results provides new knowledge that characterizes the extent to which fall severity can be reduced from the combined strategies of optimal hand and foot response to a misstep perturbation, in addition to upper body strength. Then, the biomechanical responses associated with the optimal hand and foot placement were investigated by temporal parameters. The knowledge obtained from this study is expected to inform the contribution of climbing styles to recovery in the context of a full body response after a ladder climbing perturbation. Such knowledge is critical to provide strategies for climbing practices and associated training to reduce injuries due to falls from ladders.

2. Methods

Thirty-five participants (13 females; aged 18 to 35 years; BMI of 18.6 to 30.1) completed two visits for this study. Participants completed an upper body strength assessment on

their first visit (Beschorner et al., 2018) and 30 ladder climbing trials on their second visit (Pliner et al., 2017; Pliner et al., 2019) as previously detailed. Complete data are presented for 28 participants and partial data is presented for 3 participants, due to technical equipment errors (5 participants) and participant withdrawal (2 participants). Exclusion criteria comprised 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 provided written informed consent.

Kinematic and kinetic data were captured for participants after a ladder climbing perturbation. Kinematic data were captured at 100 Hz using 47 reflective markers and a 13-camera motion capture system (Motion Analysis Raptor Corp., Santa Rosa, CA). Participants wore tight-fitting athletic clothing, standard work shoes with a raised heel, shin guards, and a safety harness. Reflective markers were placed on the participant's head (3 markers), upper trunk (6 markers), upper arms (3 per arm), lower arms (4 per arm), pelvis (4 markers), thighs (3 per thigh), shank (3 per shank), and shoes (4 per shoe). Kinetic data were captured at 1000 Hz from a load cell that was in-line with a safety harness and fall arrest system. The load cell recorded the weight supported by the safety harness.

Participants were instructed to climb an OSHA compliant, custom 12-foot vertical ladder utilizing the ladder rungs, at a comfortable but urgent pace to simulate the speed of a regular-to-busy work. Ladder rungs were circular, 32 mm in diameter, and spaced 305 mm apart. The fourth rung from the bottom of the ladder was triggered to release from the ladder siderails every four to seven climbs. Rung release was triggered when less than 5% of the participant's body weight remained on the previous rung (i.e., most of the climber's body weight was supported by the releasing rung). Participants experienced a total of 6 climbing perturbations (i.e., releasing of the 4th rung), with 3 per climbing direction. Ladder fall severity was quantified at the peak load supported by the safety harness after the climbing perturbation and normalized to body weight (Pliner et al., 2017; Pliner et al., 2019).

Hand and foot placement responses after the climbing perturbation were categorized from the kinematic data (Pliner et al., 2019). Hand placement response was found for the hand that moved during or after the climbing perturbation, or the hand that was next to move in cases where no hand movement took place during or after the climbing perturbation. Hand trajectories were captured from a single hand marker (placed on the 3rd metacarpal). Onset and offset of hand movement was quantified as a rise or fall of 10% in the hand trajectory velocity. Three primary hand placement responses were observed: 1) HM2 – hand moved two rungs from the original position; 2) HM1 – hand moved one rung from the original position; or 3) HM0 – the hand did not move from or the hand moved and returned to the original position. Foot trajectories were captured by the mid-point of three markers on the foot (placed on the 1st and 5th metatarsal and middle toe). Foot contact was quantified as an acceleration exceeding 0.5 m/s² when the foot was within a 40 mm distance of the rung's top surface in the vertical and horizontal directions. Two foot placement responses were observed: 1) Reestablished – at least one foot reestablished foot placement with a ladder rung; or 2) Not reestablished – no foot reestablished foot placement with the ladder rungs. The foot was only considered to have reestablished contact if the foot

contact was maintained until the end of the perturbation response (Pliner et al., 2017). The methods of capturing hand and foot movement and contact times were visually confirmed and determined to be reliable approaches.

Upper body strength was assessed from grip strength utilizing a commercial dynamometer (Jamar® 5030J1, Patterson Medical, Warrenville, IL). Participants stood upright with their upper arm down by their side and elbow flexed at 90°. Participants gripped two parallel bars on the dynamometer and were asked to exert their maximum grip force for 5 seconds. Participants completed 12 maximum grip force exertion trials with 6 trials per hand. A minimum of 2 minutes rest was provided between trials. Upper body strength was quantified as the mean maximum force across all trials and normalized to body weight (Beschoner et al., 2018).

The number of beneficial factors was characterized based on prior research that identified greater upper body strength, higher hand placement, and reestablished foot placement to reduce fall severity after a climbing perturbation (Pliner et al., 2017; Pliner et al., 2019). While previous research found each effect to be important separately, the combined effects of these strategies are unclear. For example, it is possible that multiple strategies would not offer benefit over one strategy if that single strategy was sufficient. Alternatively, it is possible that one strategy is insufficient and that benefits are only observed when multiple strategies are executed. In the present study, we quantified the combined occurrences of three beneficial fall recovery factors to assess their collective effect on ladder fall severity: A) Upper body strength greater than 50% of body weight; B) moving the hand up two rungs (HM2) after an ascending climbing perturbation, not moving the hand from the original position (HM0) after a descending perturbation; and C) reestablishing foot placement after a climbing perturbation (from either foot) were each classified as one beneficial fall recovery factor. The beneficial threshold for upper body strength was set to 50% of body weight, as this is the minimum strength per hand to support one's body weight with two hands. Prior research has similarly quantified grip strength in reference to a person's ability to support their body weight (Hur et al., 2012; Young et al., 2009). The number of beneficial fall recovery factors were summed for each climbing perturbation trial (minimum = 0; maximum = 3).

The temporal characteristics of hand and foot movements during or after the climbing perturbation were quantified to investigate underlying mechanisms of beneficial hand and foot placement responses. Temporal characteristics of hand movements comprised hand release, hand contact, total hand movement, and one-point of contact time. For the HM0 responses, temporal analyses could only be conducted if the hand moved and then regripped the rung (26% of HM0 responses resulted in hand movement).

Hand release and hand contact were quantified with respect to perturbation onset. Hand release was the time from perturbation onset to hand offset (hand offset – perturbation onset). Negative hand release times are indicative of the hand leaving before perturbation onset (i.e., the amount of time the hand is airborne before perturbation onset). Positive hand release times are indicative of the hand leaving after perturbation onset (i.e., the amount of time that passes after perturbation onset before the hand moves). Hand contact was the

time from perturbation onset to hand onset (hand onset – perturbation offset). One-point of contact time was characterized when only one hand or foot was in contact with the ladder. This time period always occurred after perturbation onset (when feet are no longer in contact with the ladder) and while the hand was moving. In cases where the hand released before perturbation onset, the one-point of contact time was from perturbation onset to hand contact (hand contact – perturbation onset). In cases where the hand released after perturbation onset, the one-point of contact time was from hand release to hand contact (hand contact – hand release). In 11 cases, maintained foot contact occurred before hand contact. In these cases, time of foot contact replaced hand contact. Hand movement time was the time from hand release to hand contact (hand contact – hand release).

Foot contact with a ladder rung after the climbing perturbation occurred in the majority of cases (51% across both feet) but either foot only maintained contact with the rung in 76% of foot contact cases (39% of total cases). In the other 24% of foot contact cases, the foot slipped off the rung after foot-rung contact. The time from perturbation onset to foot contact (referred to as foot flight time) was quantified to assess its relationship with the outcome of slip or maintained foot contact.

To assess the collective effect of beneficial fall recovery factors on ladder fall severity, an ANOVA was performed with the number of beneficial fall recovery factors as the predictor variable (nominal) and normalized harness force as the dependent variable. Participant was included in the model as a random variable. Tukey's HSD was used for post-hoc comparisons if the number of beneficial fall recovery factors was found to be significant. In addition, a linear regression was performed on normalized harness force (dependent variable) with the occurrence of each beneficial fall recovery factor as the predictor variable to assess the individual effect of each beneficial fall recovery factor. Occurrence of each beneficial fall recovery factor was set to 1, whereas no occurrence of the beneficial fall recovery factor was set to 0. The unstandardized and standardized beta coefficients are reported to show the normalized harness force reduction per beneficial fall recovery factor. A square root transform was performed on normalized harness force to achieve normally distributed residuals. Pearson's bivariate correlations were obtained to assess the correspondence between each beneficial recovery factor. Bivariate correlations were performed on the occurrence of optimal hand and foot placement; optimal hand placement and upper body strength greater than 50% body weight; and optimal foot placement and upper body strength greater than 50% body weight.

ANOVAs were performed for each temporal measure with hand placement response as the predictor variable. ANOVAs were performed separately for each climbing direction. Tukey HSD post-hoc analyses were performed when temporal measures significantly differed by hand placement response. Finally, logistic regressions were performed with foot flight time as the predictor variable and slip outcome as the dependent variable to determine the influence of time to foot contact on maintaining foot contact. Logistical regressions were performed separately by climbing direction.

3. Results

Data were assessed for 31 participants. Fourteen participants (45%) had an upper body strength greater than 50% of their body weight. Optimal hand (HM2 response) occurred 27 times after 87 ascending perturbations (31%). Optimal hand (HM0 response) occurred 13 times after 80 assessed descending perturbations (24%). Foot reestablishment from either foot occurred after 57 (65%) and 54 (68%) ascending and descending perturbations, respectively.

The number of beneficial fall recovery factors was assessed for 167 ladder climbing perturbations. The occurrence of all three beneficial recovery factors occurred the least (10%), followed by the occurrence of no beneficial recovery factors (14%). One beneficial recovery factor after a climbing perturbation had the highest occurrence (45%), followed by the occurrence of two beneficial recovery factors (31%). The occurrence of optimal hand and foot placement response was similar between individuals with upper body strength greater and less than 50% of bodyweight (Supplementary Material – Table 1). A significant correlation between the occurrence of beneficial recovery factors was not found ($r_{167} < 0.1$; $p > 0.05$).

There was a significant reduction in normalized harness force with each beneficial fall recovery factor as indicated by the ANOVA ($F_{3,163}=15.1$; $p < 0.001$) (Figure 1) and regression analysis ($F_{3,163}=15.9$; $R^2=0.227$ $p < 0.001$) (Table 2 and Supplementary Material – Figure 1). Achieving three beneficial fall recovery factors resulted in significantly lower normalized harness force than achieving two (Tukey HSD: $p=0.030$), one (Tukey HSD: $p < 0.001$), and zero (Tukey HSD: $p < 0.001$) beneficial fall recovery factors. Achieving two beneficial fall recovery factors resulted in a similar normalized harness force as achieving one beneficial fall recovery factor (Tukey HSD: $p=0.201$) and a lower normalized harness force than achieving no beneficial fall recovery factors (Tukey HSD: $p < 0.001$). Achieving one beneficial fall recovery factor resulted in a lower normalized harness force than achieving no beneficial fall recovery factors (Tukey HSD: $p=0.001$). Optimal hand placement (standardized $\beta=-0.260$; $t_{166}=3.7$; $p < 0.001$) had the greatest reduction in normalized harness force, followed by reestablished foot placement (standardized $\beta=-0.249$; $t_{166}=3.6$; $p < 0.001$), then upper body strength greater than 50% body weight (standardized $\beta=-0.244$; $t_{166}=3.5$; $p < 0.001$).

All temporal hand movements were affected by hand placement response after an ascending perturbation (Figure 2a). Specifically, hand release time ($F_{2,43}=14.5$; $p < 0.001$) occurred significantly earlier for the HM2 response than the HM1 (Tukey HSD: $p=0.013$) and HM0 (Tukey HSD: $p < 0.001$) response. Hand contact time ($F_{2,43}=9.2$; $p < 0.001$) occurred significantly later for the HM1 response than the HM2 response (Tukey HSD: $p < 0.001$) and later for the HM1 response than HM0 response, but the post-hoc analysis was not significantly different (Tukey HSD: $p=0.057$). One-point of contact time ($F_{2,43}=11.0$; $p < 0.001$) was significantly longer for the HM1 response than the HM2 (Tukey HSD: $p < 0.001$) and HM0 (Tukey HSD: $p < 0.001$) response. Hand movement time ($F_{2,43}=12.3$; $p < 0.001$) was significantly shorter for the HM0 response than the HM1 (Tukey HSD: $p < 0.001$) and HM2 (Tukey HSD: $p=0.001$) response.

All temporal hand movements, except hand contact time ($F_{2,63}=2.3$; $p=0.112$), were affected by hand placement response after a descending perturbation (Figure 2b). Specifically, hand release time ($F_{2,63}=7.6$; $p=0.001$) occurred significantly later for the HM0 response than the HM1 (Tukey HSD: $p=0.039$) and HM2 (Tukey HSD: $p=0.001$) response. One-point of contact time ($F_{2,63}=15.4$; $p<0.001$) was significantly shorter for the HM0 response than the HM1 (Tukey HSD: $p=0.001$) and HM2 (Tukey HSD: $p<0.001$) response. In addition, the one-point of contact time was significantly shorter for the HM2 response than the HM1 response (Tukey HSD: $p=0.044$). Hand movement time was significantly different across all hand placement responses ($F_{2,63}=91.2$; $p<0.001$), with longer movement times during the HM1 response than the HM2 (Tukey HSD: $p<0.001$) and HM0 (Tukey HSD: $p<0.001$) response. In addition, hand movement times were longer for the HM2 response than the HM0 response (Tukey HSD: $p<0.001$).

Earlier foot-rung contact time (shorter foot flight time) was associated with a contact slip outcome after an ascending (Wald=5.9; $p=0.015$) and descending (Wald=11.4; $p<0.001$) climbing perturbation. Longer foot flight times increased the probability of maintained foot contact after an ascending (Figure 3a) and descending climbing perturbation (Figure 3b). The logistic regression equations for the slip risk are provided in Figure 3.

4. Discussion

We investigated strategies associated with reduced fall severity, in order to inform climbing styles and full body responses that are beneficial to recovery from ladder climbing perturbations. Specifically, we found that each additional beneficial strategy that climbers executed led to incrementally better recovery outcomes. In addition, we discovered that hand placement strategy was related to hand movement times and that foot placement strategy was related to the amount of time between perturbation onset and foot-rung contact.

Fall risk from a misstep decreased progressively with increasing number of beneficial fall recovery factors among upper body strength, optimal hand placement, and reestablished foot placement after a climbing perturbation. By utilizing zero or one beneficial factor, 55% or 36% of the body weight had to be supported by the harness, respectively. By utilizing two or three beneficial factors, only 22% and 8% of the body weight had to be supported by the harness, respectively. These percentages are further supported by the regression analysis, revealing the use of each beneficial fall recovery factor to contribute to a 13% to 20% reduction of body weight supported by the harness. Other researchers have utilized a harness force cutoff value of 30% body weight to characterize a fall after slip events during level walking (Yang & Pai, 2011). Thus, achieving at least two beneficial fall recovery factors is deemed meaningful to arresting a fall from a misstep during ladder climbing and contributing to ladder user safety.

We found that the optimal hand placement can be achieved by maintaining a high hand hold with an extended arm as often as possible. This upper limb posture may be preferred as it is associated with the highest pull strength (Beschorner et al., 2018; Hur, Motawar, & Seo, 2014; Seo et al., 2010). Achieving this upper limb posture as often as possible means that the hand moves up toward the next rung *earlier* during ascent, and the hand moves

down to the next rung *later* during descent. The optimal hand placement was associated with faster hand reestablishment on the rung and a shorter duration of 1-point of contact after the perturbation. While climbing a ladder by grasping rungs, climbers have only two points of contact for approximately half the time, which represents a vulnerable time in case of a foot or hand slip (Fu et al., 2022; Jensen & Holland, 2020). This optimal hand placement is expected to be beneficial to achieve the bilateral hand grip for recovery from a misstep ladder fall. Indeed, achievement of the optimal hand placement resulted in a significant reduction in the fall severity as shown in the regression analysis.

Hand release times occurred before perturbation onset in cases when the hand moved two rungs (HM2) and after perturbation onset when the hand elevated and returned to the initial rung (HM0). Climbers that moved their hand one rung (HM1) had the greatest time periods where only one limb was in contact with the ladder (one-point of contact). HM1 response may have taken longer to execute due to a change in target trajectory, compared to HM2 response which is the normal hand movement during unperturbed climbing (Flash & Henis, 1991; Reichenbach et al., 2009). This observation may explain why the HM1 response is associated with increased fall severity (Pliner et al., 2019). Hand placement response may be dictated by when the perturbation occurs relative to hand movement and may explain differences in fall severity across hand placement responses.

We further found that foot reestablishment was achieved more often when more time was allotted before foot-rung contact. Foot slip outcomes were associated with an earlier foot contact time, which may be due to a reduced time to actively adjust foot positioning for an optimal foot-rung placement to stabilize the body at the time of foot contact. Prior research has indicated that approximately 200–300 ms is required for non-elderly adults to begin altering the trajectory of their foot in reactive stepping tasks (Moraes et al., 2007; Young & Hollands, 2012). This value approximately aligns with the shift from the foot slipping to the foot making successful contact with the rung (Figure 3). However, too long of a foot flight time may also be adverse since this is more time that support forces from the foot are delayed or never occur as then only the upper body forces may resist the body from falling.

The limitations of this study are that repeated perturbations occurred 6 times for each participant, and thus some participants may have changed the climbing pattern after the first perturbation to adjust for a potential perturbation. In addition, the perturbation in this study is most reflective of a foot slip or misstep event. Translation of these results to other ladder fall causes may be limited. The participants were relatively younger compared to the construction worker population and older adults who experience ladder falls in residential settings. Thus, further investigation is needed to examine effects of the age-related factors such as diminished bodily sensation or slower reaction that may influence response to perturbation (Hur, Motawar, & Seo, 2014; Hur, Wan, & Seo, 2014; Motawar et al., 2016). In addition, an upper body strength threshold of 50% body weight was deemed beneficial in this study. This threshold is the minimum upper body strength required to arrest a ladder falling event from upper body strength alone (capability of supporting one's body weight with both hands). This threshold may not be sufficient in all ladder falling events. Only vertical ladder climbing was investigated in the present study, while varying slant angles and handrails may be used for various ladder usage scenarios in the field (Fu et al., 2022;

Jensen & Holland, 2020; Lee et al., 1994). In addition, workers typically carry loads of work-related tools (Fu et al., 2022; Simeonov et al., 2020), which were not included in the present study.

The knowledge obtained from this study contributes to the body of literature for strategies to prevent falls from ladders ranging from ladder and handhold design (Beschoner et al., 2018; Fu et al., 2022; Hur et al., 2012; Hur, Motawar, & Seo, 2014; Seo & Armstrong, 2009; Simeonov et al., 2020; Young et al., 2009; Young et al., 2012), responses to perturbation (Pliner et al., 2020; Pliner et al., 2017; Pliner et al., 2019), and performance augmentation (Hur, Wan, & Seo, 2014; White et al., 2018). Specifically, the present study contributes new knowledge regarding the summative benefits of multiple strategies and biomechanical kinematics of temporal full body response mechanisms for recovery from a ladder climbing perturbation. Translation of this knowledge to improve ladder safety may be in the form of: 1) monitoring and increasing upper body strength of ladder users; 2) training the temporal behavior of ladder climbing that promotes optimal hand and foot placement response in the event of a climbing perturbation; and 3) optimizing ladder design to reduce the need of upper body strength for recovery and increase the likelihood of beneficial recovery strategies. Together, these collective findings may inform training strategies for best climbing practices and/or ladder design to reduce injuries due to falls from ladders, which is prevalent in construction workplaces (U.S. Department of Labor, 2022b) and residential settings (Aldailami et al., 2022; Hamdard et al., 2023; Jain et al., 2014).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Occupational Applications

Falls from ladders remain a significant cause of injuries in workplaces as well as residential settings. While recent research reveals factors related to fall severity from a ladder, strategies that workers can adopt to minimize fall severity are not well understood. Results from our current study indicated that increased upper limb strength, achieving a higher hand hold, and controlled re-establishment of the foot on the rung have summative benefits to reduce fall severity and increase recovery from a misstep perturbation. Ensuing adequate upper limb strength among workers and training workers to climb ladders leading with hand placement during ascent and foot placement during descent can facilitate these beneficial strategies to arrest a ladder fall.

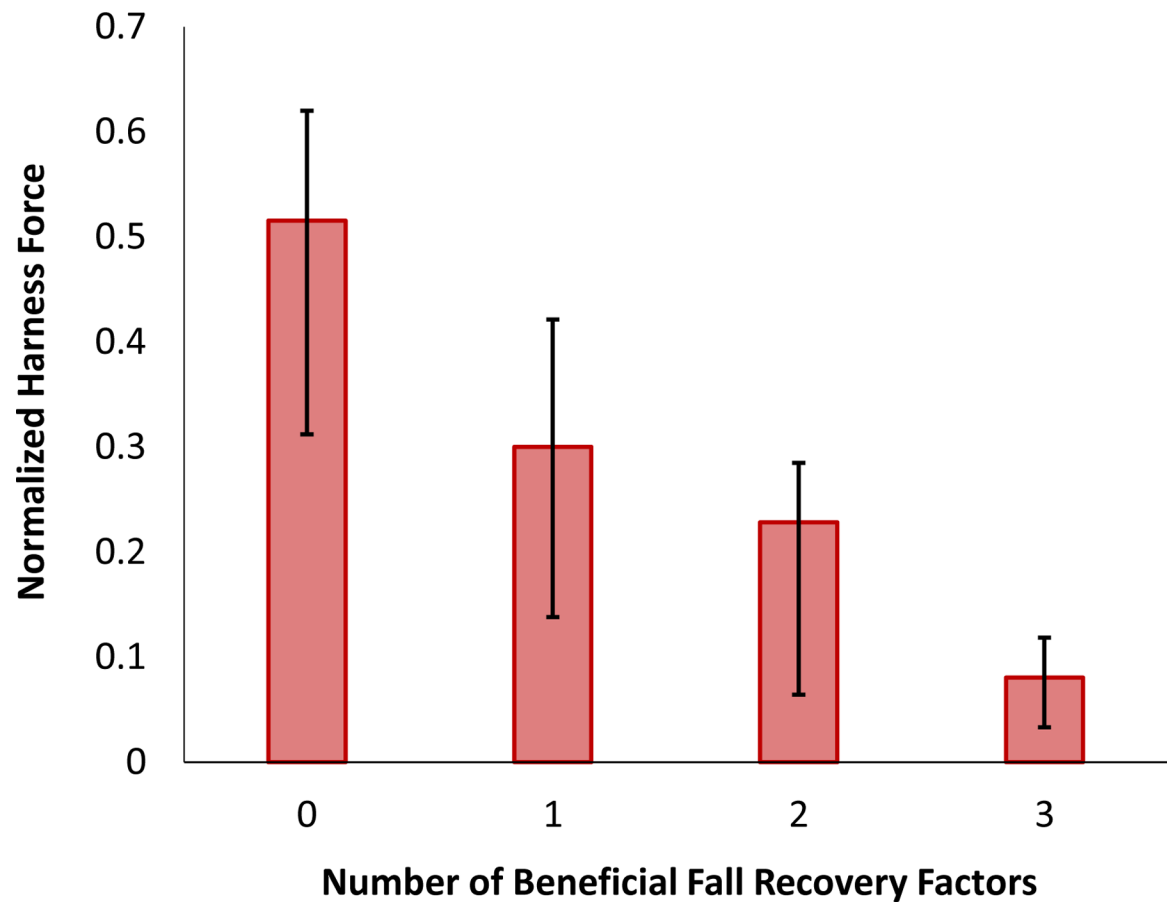


Figure 1.

Normalized harness force by the number of beneficial fall recovery factors after a climbing perturbation. Participants with more beneficial recovery factors have a lower harness force (better recovery response), reducing the likelihood of a fall. Negative and positive error bars represent the first and third quartile ranges, respectively.

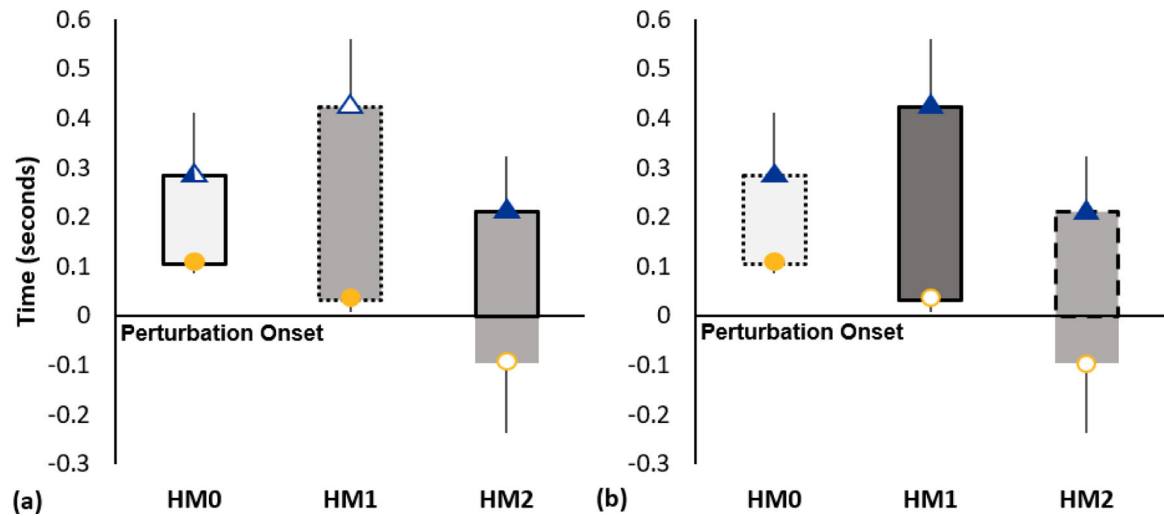


Figure 2.

Mean hand release (yellow circle), hand contact (blue triangle), total hand movement (length of gray square), and 1-pt. of contact (visual estimate from length of square outline patterns) times for hand placement (HM) response after ascending (a) and descending (b) climbing perturbations. Variation in shape shades and outlined patterns denote significantly different times between hand placement responses. Time zero represents perturbation onset. HM2 – hand moved two rungs from initial position; HM1 – hand moved one rung from initial position; HM0 – hand elevated and returned to initial position. Negative values for the hand release time indicate the hand left the rung prior to perturbation onset. Error bars represent standard deviations for hand release (negative bars) and hand contact (positive bars) times.

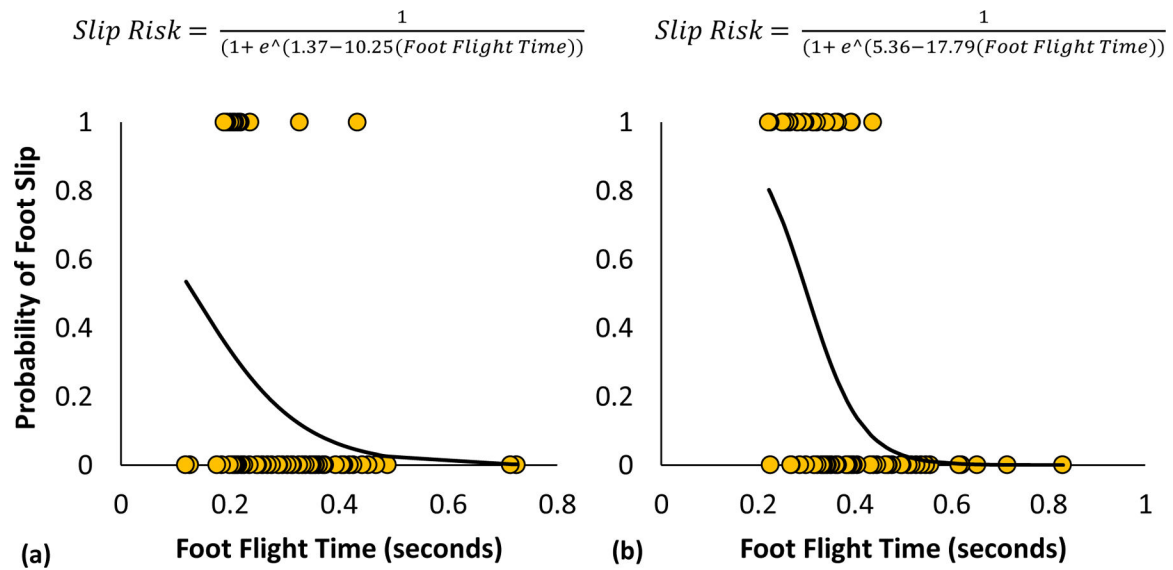


Figure 3.

Probability of a foot slip after foot-rung contact across foot flight time for contact/slip (yellow dots = 1) and maintained contact (yellow dots = 0) outcomes after an ascending (a) and descending (b) perturbation. Logistical regressions and equations of foot slip probability are plotted on the graphs.

Table 1:

Summary of previous related work (analysis and outcome) and the knowledge gap in this work.

Publication	Analysis	Outcome
Pliner et al. (2019)	Assessed fall severity (continuous) by hand and foot placement response (categorical) and upper body strength (continuous) after a ladder climbing perturbation.	Found a higher hand placement response to reduce fall severity. Found reestablished foot placement to reduce fall severity. Found greater upper body strength to be associated with reduced fall severity.
Pliner et al. (2020)	Assessed kinetic biomechanical hand-rung force (continuous) relationship with upper body strength (continuous) and fall severity (continuous) after a ladder climbing perturbation.	Found greater fall severity to be associated with higher hand-rung forces. Did not find upper body strength to strongly influence hand-rung force.
Knowledge gap in this previous work		
This manuscript's novel contribution	The summative effect of beneficial fall recovery factors (optimal hand and foot placement response, upper body strength greater than 50% body weight) on fall severity. The kinematic biomechanical responses associated with optimal hand and foot placement response.	

Table 2:

Unstandardized and standardized beta coefficients of beneficial fall recovery factors on normalized harness force.

	Unstandardized β	Standardized β	<i>t</i> -statistic	<i>p</i> -value
Optimal Hand Placement	−0.146	−0.260	3.7	<0.001
Reestablished Foot Placement	−0.128	−0.249	3.6	<0.001
Upper Body Strength > 50% Body weight	−0.118	−0.244	3.5	<0.001