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Effects of upper body strength, hand placement and foot placement on ladder fall severity

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Highlights (3 to 5 bullets, only 85 characters)

- Assessed the effects of strength, hand and foot placement on ladder fall severity
- Participants were exposed to unexpected perturbations during ladder climbing
- Higher hand placements reduce fall severity after a climbing perturbation
- Reestablishing a foot reduces fall severity after a climbing perturbation
- Greater upper body strength is associated with lower fall severity

Abstract

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

Keywords: ladder climbing; slips, trips and falls; upper extremity; postural response

Word Count: 2,979

1. Introduction

The majority of fatal fall injuries are from a height [1]. Fatal fall injuries have increased 26% from 2011 to 2016 with the plurality of these injuries occurring from a ladder [2]. Understanding potential strategies to prevent falls from a ladder is important to reduce fatal falls and disabling injuries.

Upper body strength is considered to be an important factor that contributes to arresting a fall from a ladder. Not all individuals are capable of generating enough force to support their full body weight with one hand [3, 4]. Also, prediction models of a person's ability to stop a downward fall suggest that individuals with higher upper body strength are more likely to recover [5]. However, the relevance of upper body strength in preventing ladder falls has not been demonstrated in actual ladder climbing perturbation studies.

Other factors that influence recovery or fall severity include the response of the upper and lower body to a perturbation. The placement of the hands may be important to recovery since the hands stabilize the climber during ladder climbing by pulling the climber towards the ladder [5, 6]. Furthermore, the hands contribute to balance recovery by applying vertical forces after a perturbation during climbing [3, 4]. Preliminary observations of responses to a perturbation during ladder climbing have revealed multiple hand placement responses occur to re-grasp a handhold [7]. Hand placement response may affect recovery during a fall from a ladder, similar to the impact of the trailing leg response on recovery during gait slip perturbations [8, 9]. Characterizing hand placement responses and their effect on recovery from a climbing perturbation could guide interventions for preventing falls from ladders.

Reestablishing the feet may be another important factor to arrest a fall after a perturbation during ladder climbing. The lower body supports the majority of the climber's weight during ladder climbing [6]. Also, the foot placement on the rung affects the climber's risk of slipping [10]. The lower-limb muscles actively respond to a climbing perturbation [11], indicating that replacing the feet on the ladder may be part of the active balance recovery response.

While these factors were suggested to influence fall severity in literature, there currently exists little evidence demonstrating their impact on fall risk during ladder climbing. Therefore, the purpose of this study was to determine the effect of upper body strength, hand placement and foot placement on fall severity after a ladder climbing perturbation. This study quantified differences in fall severity predictions between upper body strength measurements using a laboratory equipment setup [3-5] and a portable grip dynamometer. A dynamometer grip strength test is considered more practical since it can screen individuals *on site* to intervene for the highest risk individuals.

2. Methods

This study consisted of an upper body strength testing session [12] and exposure to perturbations during a ladder climbing testing session [13], performed on separate days. Thirty-five participants between the ages of 18 and 35 years participated. Seven participants were excluded from the data analysis due to equipment malfunction or participant withdrawal. This study analyzed data on 28 participants including 17 males (23.8±4.6 yrs., 81.8±8.7 kg, 1.8±0.1 m) and 11 females (25.2±6.4 yrs., 62.7±6.2 kg, 1.7±0.1 m). Approval was obtained by the Institutional Review Board and testing was performed at the University of Wisconsin-Milwaukee. Informed consent was obtained prior to each testing session. Those with musculoskeletal disorders, previous shoulder dislocations, osteoporosis/osteoarthritis, neurological/cognitive disorders, balance disorders, or pregnancy were excluded. This study represents a secondary analysis of primary analyses [12, 13] to assess a potential link between individual strength and recovery from a perturbation during ladder climbing.

2.1 Testing Session 1: Upper Body Strength

During the first session, breakaway strength (peak force applied to a rising rung prior to the hand decoupling) and grip strength on a dynamometer were measured. The breakaway strength test was performed using a custom-laboratory-based apparatus involving an aluminum cylindrical rung (diameter: 32 mm) in-line with a motorized pulley system and load cell [3, 12]. The load cell measured the force applied to the rung by the hand (1 kHz) while the motor pulled the rung out of the hand (i.e. breakaway) [12]. Grip strength was measured utilizing a commercially available dynamometer (Jamar® 5030J1, Patterson Medical, Warrenville, IL). Participants stood upright with their shoulder neutral and elbow flexed at 90° and exerted their maximum grip force between the two parallel bars on the dynamometer for five seconds, consistent with the duration for the breakaway strength test. For each strength test, two repeated trials were performed for each hand (left and right) and each of three glove conditions (bare hands, cotton gloves, latex-coated gloves). The maximum force recorded for each trial was averaged across all twelve trials to determine a participant's breakaway and grip strength. The impact of glove condition was previously reported [3, 12] and is not considered in this study. All strength measurements were normalized to body weight.

2.2 Testing Session 2: Ladder Climbing

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

Participants were instructed to climb a 12-foot, vertical ladder at a comfortable but urgent pace to simulate climbing speed of a regular-to-busy work day. The ladder was custom-built in compliance with the U.S. Occupational Safety and Health Administration (OSHA) standards. The rung diameter was 32 mm, consistent with the rung dimensions/material used in testing session 1, and rungs were spaced 305 mm apart [14]. Five reflective markers were placed on the ladder to determine the ladder's position relative to the climber. Participants experienced a total of six ladder climbing perturbations, in each climbing direction (ascent, descent) and for the three glove conditions. Participants practiced climbing the ladder until they were comfortable in each climbing condition. Order of climbing perturbation was randomized. Prior to each climbing perturbation, climbers performed regular climbs three to six times (with the exact number randomly chosen and unknown to the participants) to reduce anticipation of a perturbation. The perturbations resembled a ladder misstep and were generated by decoupling the fourth rung from the ladder rails shortly after foot contact. This time point was consistent with the time when a person's foot is most likely to slip off of a ladder rung [11, 13].

Ladder fall severity was quantified from the load supported by the harness. The peak harness force was found between perturbation onset and end of the perturbation response and normalized to body weight [13]. A higher harness force was interpreted as a greater likelihood of the perturbation resulting in a fall. Harness force data was filtered using a zero-lag, 4th order low-pass Butterworth filter with a cut-off frequency of 36 Hz [15]. Nine trials were removed due to incongruence between the end of perturbation response identified by an algorithm [13] and visual inspection.

Three common hand placement responses and three foot placement responses were observed. Most participants established two hands in contact with the ladder rung(s) by the end of the perturbation, but the placement of hands varied across trials (Figure 1). The three most frequent hand placement responses were: HM2 – hand moved two rungs (Figure 1.a, consistent with unperturbed climbing), HM1 – hand moved one rung (Figure 1.b), HM0 – the hand did not move to a different rung (Figure 1.c). The movement direction was consistent with the climbing direction (i.e. HM2 would signify the hand moved two rungs up for ascent or two rungs down for descent). The two foot placement responses were: reestablished – one or both feet reestablished contact with the ladder rung(s) (Figure 1.d), and not reestablished – neither foot reestablished contact with the ladder rungs (Figure 1.e). In nine of the trials, other hand placement strategies were observed including the hands decoupling from the rung that was grasped (4 trials, decoupled), the moving hand failing to reestablish hand contact until after the end of perturbation response (i.e. peak harness force) (3 trials, hand not reestablished), or the hand moved three rungs (2 trials, HM3). Normalized harness force data of these trials were reported but not included in the statistical analysis due to their rarity.

Hand placement response was found for the hand that was either moving or about to move during perturbation. Hand movement onset and offset were identified when the vertical velocity of the 3rd metacarpal marker exceeded and fell, respectively, below 10% of the metacarpal's peak velocity from the hand's prior movement [11]. Foot contact was identified if the vertical deceleration of the foot (midpoint between 1st and 5th metatarsal and middle toe markers) exceeded 0.5 m/s^2 when the foot was within a 40 mm distance of the rung's top surface in the vertical and horizontal direction. The foot was only considered to have reestablished contact if the foot maintained contact (i.e. did not slip off) until the end of the perturbation, which was confirmed visually. Acceleration data was used to classify foot-rung contact because the foot hit the rung at various velocities that could not be correctly categorized by a velocity threshold. Position data was filtered using a zero-lag, 2nd order Butterworth low-pass filter with a cut-off frequency of 10 Hz [11] and differentiated to calculate velocity and acceleration.

2.3 Statistical Analysis

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

3. Results

The average (standard deviation) normalized harness force was 0.28 (0.25) after a climbing perturbation (corresponding to 28% body weight). The average (standard deviation) normalized breakaway strength and grip strength was 0.74 (0.19) and 0.51 (0.10), respectively. The prevalence of hand and foot placement responses varied across ascending and descending perturbations (Figures 2,3).

In both repeated measures ANOVA models (i.e., breakaway strength and grip strength), climbing direction, hand placement, foot placement, upper body strength, and climbing direction x hand placement affected normalized harness force. No other interaction effects in either model were statistically significant (Table 1).

Since the climbing direction x hand placement interaction was significant, a post-hoc ANOVA model was performed to determine the effect of hand placement on ascent and descent. During ascent, moving the hand one rung up (HM1) was associated with greater normalized harness forces than moving the hand two rungs up (HM2) and ending at the starting rung (HM0) ($p<0.001$; $F_{2,76}=8.386$) (Figure 2.a). During descent, moving the hand two rungs down (HM2) was associated with a greater normalized harness forces than hand responses where the hand moved only one rung down (HM1) or ended at the starting rung (HM0) ($p<0.001$; $F_{2,68}=9.865$) (Figure 2.b). Reestablishing at least one foot back onto the rung (mean: 0.24; standard deviation: 0.21) was associated with lower harness forces than not reestablishing a foot (mean: 0.34; standard deviation: 0.25) (Figure 3). Hand placement of decoupled and HM3 resulted in higher normalized harness forces than other hand placement responses with the exception of one case in which the person's hand decoupled while reestablishing their feet during descent (no statistics performed, Figure 3.b). Interestingly, participants who experienced a decoupling between the hand and the rung (decoupled) had low-to-moderate upper body strength (53% to 63% of body weight) (no statistics performed). Cases in which participants voluntarily released a rung and did not grasp another rung (hand not reestablished) by the end of the trial had generally lower harness forces than the other hand placements (Figure 2).

Normalized harness force was negatively correlated (low-to-moderate) with breakaway strength ($p=0.001$; $\rho=-0.264$) (Figure 4.a) and grip strength ($p<0.001$; $\rho=-0.329$) (Figure 4.b). When comparing models with breakaway strength vs. grip strength, the models yielded similar predictions of ladder fall severity, producing the same adjusted R^2 value ($R^2=0.69$). This indicates grip strength to be as good of a predictor of ladder fall severity as breakaway strength.

Discussion

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

An increase in upper body strength was associated with lower fall severity. Breakaway strength and grip strength were both significant predictors of ladder fall severity. Both active (finger flexion) and passive (frictional) forces contribute to breakaway strength, whereas only the active (finger flexion) forces contribute to grip strength (see Supplementary Figure 1 for variation between strength measures) [3, 16, 17]. The passive forces due to friction have been previously thought to be important to ladder recovery, which would suggest that breakaway strength would better predict fall risk [3, 4, 16, 17]. However, the results of this study do not support this view. We should note, however, that the harness system used in this study typically caught participants before their hands fully decoupled from the rung and that breakaway strength might become more relevant in the absence of the harness system [13]. In addition, participants gripped the ladder rungs (i.e. horizontal orientated handhold) in this experiment and passive forces are likely more important when grasping rails (i.e. vertically orientated handholds). Therefore, this finding should be further monitored. Nevertheless, the results of this study are encouraging since grip strength tests are easier and less expensive to administer than breakaway strength. Low-to-moderate strength individuals appear to be at risk of their hand decoupling from the rung after a ladder climbing perturbation. Therefore, simple grip strength assessment may be used to identify and target interventions to individuals at greater ladder fall risk.

The role of hand placement on fall severity may be due to a combination of factors. The hand placement after a climbing perturbation may be the net effect of the hand's position at perturbation onset, the active response of the upper body after perturbation onset, and the dynamics of the body during falling. Differences in fall severity by hand placement may be partially attributed to the amount of force a hand can generate in different arm postures [12] and the time available to generate force. The upper body's capacity to generate pulling force increases with a higher hand placement relative to the body [12]. During ascending climbs, having a mid-reach arm posture (HM1) after a perturbation may have limited the amount of upper body pulling force that could be generated compared to HM2. One explanation for why this same effect was not observed in HM0, is that the hand may spend more time in contact with the rung for this response [18]. Thus, HM1 may be a response that neither benefits from the strength advantage of a higher reach nor the large time in contact that may be occurring with HM0. The lower fall severities for HM0 and HM1 during descending climbs, may similarly be linked with having a higher hand position. Once again, this would lead to a higher upper body force generation capacity, compared to HM2. While no statistical analysis was performed, the higher harness forces that were generally associated with the decoupling hand placement responses (decoupled) suggests that reestablishing the hands back onto the ladder rungs may be a critical component of arresting a ladder falling event.

Reestablishing at least one foot onto the ladder rung, and ascending perturbations (compared to descending) were associated with a lower fall severity. Reestablished foot placement likely reduced fall severity by supporting the climber's body weight consistent with unperturbed climbing [6]. Higher fall severity during descent compared with ascent was previously discussed for this data set in one of our earlier papers [13].

Possible interventions may be informed by the results of this study. First, strength-building or weight loss interventions may be valuable for lower-strength individuals or individuals that have more bodyweight to support. Climbers may also benefit from leading with their hands during ascending climbs and leading with their feet during descending climbs to promote a more elevated hand position. In addition, interventions that optimize ladder design (e.g. rung spacing, ladder angle) may improve a climber's ability to reestablish foot placement.

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

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

Conflict of Interest

None.

Acknowledgements

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Figure captions

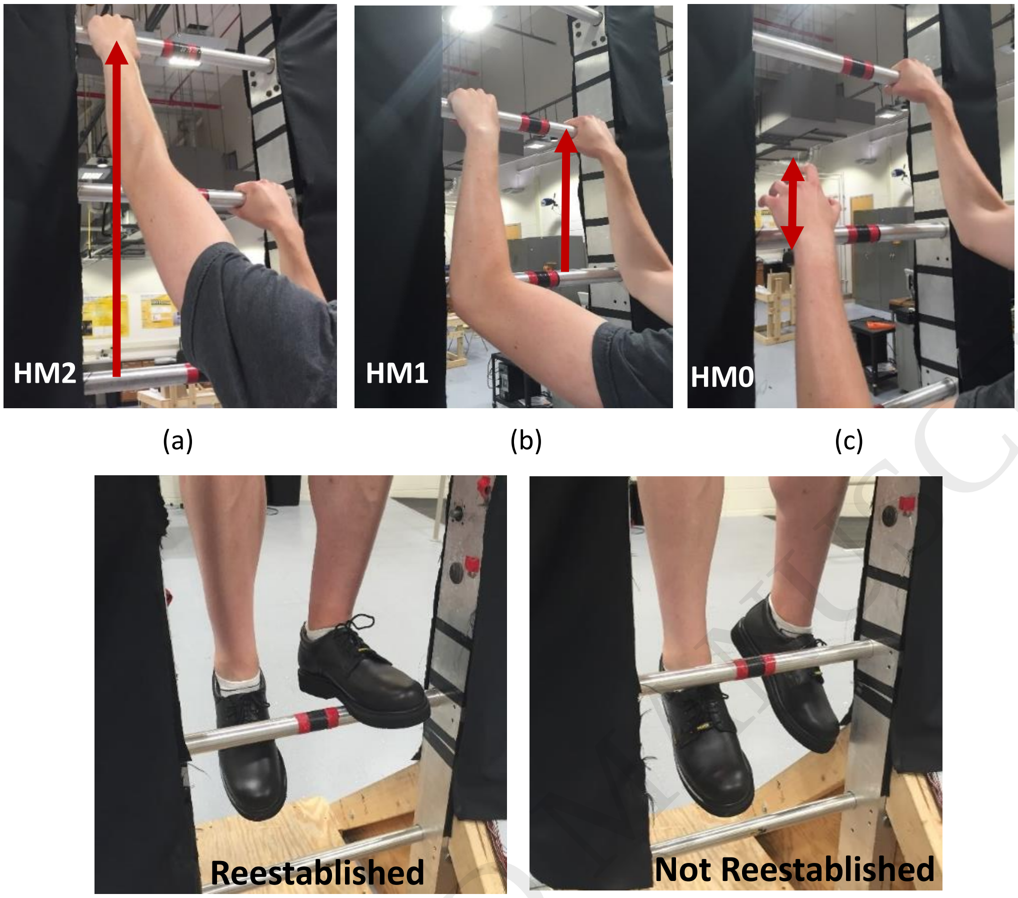
Figure 1: The most common hand placement responses included: a) hand moved two rungs, b) hand moved one rung, and c) hand ended at starting position. Foot placement responses included d) at least one foot reestablished contact with the ladder rung and e) no foot reestablished contact with the ladder rung.

Figure 2: Average normalized harness force across hand placement responses during a) ascending and b) descending perturbations. Standard deviation of normalized harness force is represented by the positive error bars and standard error of normalized harness force is represented by the negative error bars. Occurrence (percentage) of each hand placement response is displayed on the horizontal axis below each hand placement response label. Note statistical analysis was not performed for trials where the hand moved three rungs (HM3), decoupled from the rung (decoupled), or left the rung, but did not reestablish hand contact prior to end of perturbation response (hand not reestablished) (white bars). N.A. indicates that no data was recorded for that condition.

Figure 3: Average normalized harness force for hand and foot placement combinations after a) ascending and b) descending perturbations. Certain hand placement outcomes were not included in the statistical analyses including HM3, decoupled or hand not reestablished (outlined bars). Data elements, where the foot reestablished contact, are represented by the dark gray bars and data elements, where the foot did not reestablish contact, are represented by the light gray bars. Occurrence (percentage) of each foot placement response is displayed under the legend below each foot placement response label. N.A. indicates that no data was recorded for that condition.

Figure 4: Relationship between the average normalized harness force with a) breakaway strength and b) grip strength. Each dot represents a person's average normalized harness force across all six perturbations. Male participants are represented by the gray dots and female participants are represented by the solid darker dots. The solid line represents the best linear fit. Spearman's correlations (ρ) are displayed on each graph.

Figure 1



(a) (b) (c)

(d) (e)

Figure 2

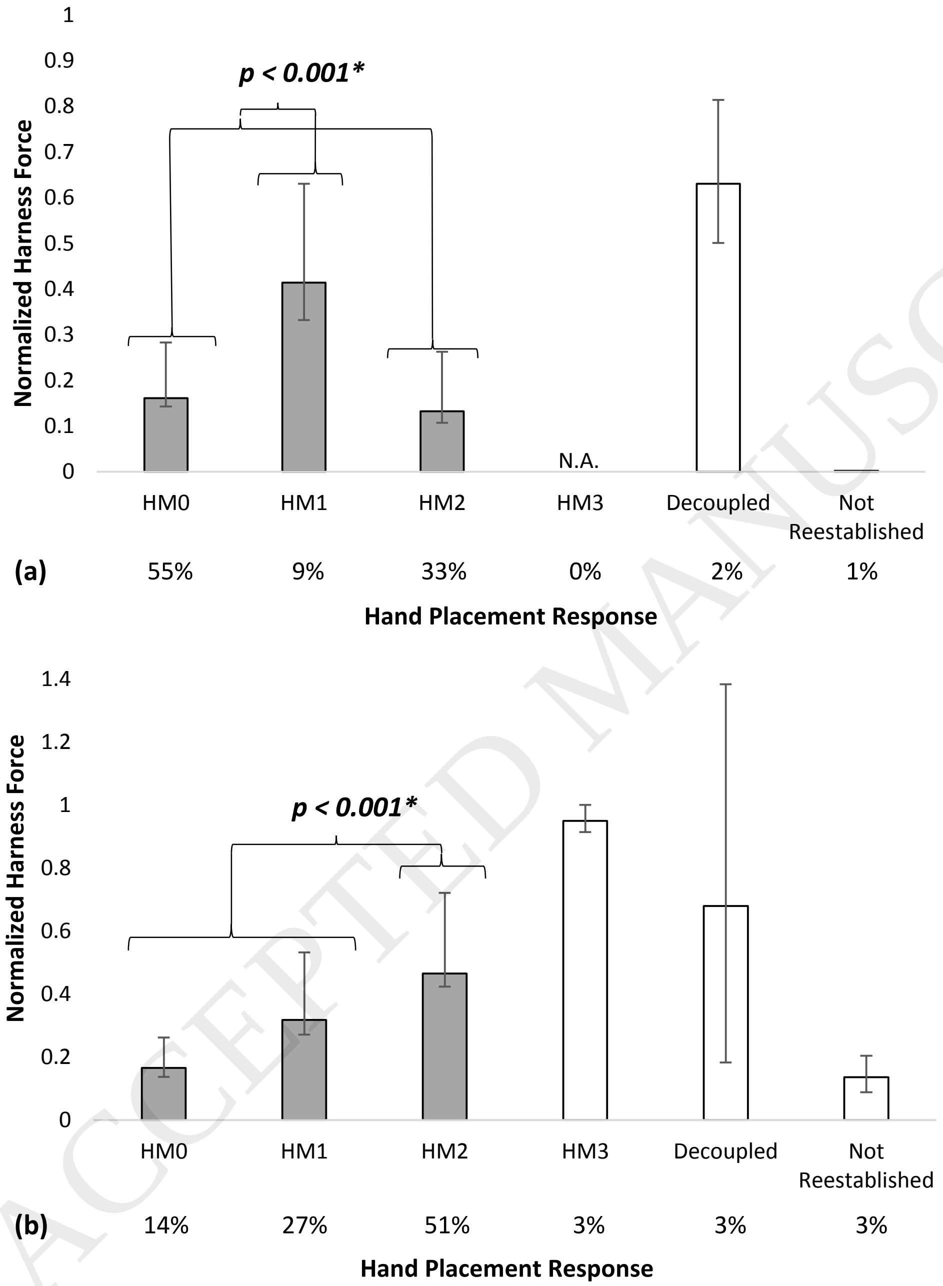

Normalized Harness Force
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
p < 0.001*
N.A.
HM0
HM1
HM2
HM3
Decoupled
Not Reestablished
(a)
55%
9%
33%
0%
2%
1%
Hand Placement Response
Normalized Harness Force
1.4
1.2
1
0.8
0.6
0.4
0.2
0
p < 0.001*
HM0
HM1
HM2
HM3
Decoupled
Not Reestablished
(b)
14%
27%
51%
3%
3%
3%
Hand Placement Response

Figure 3

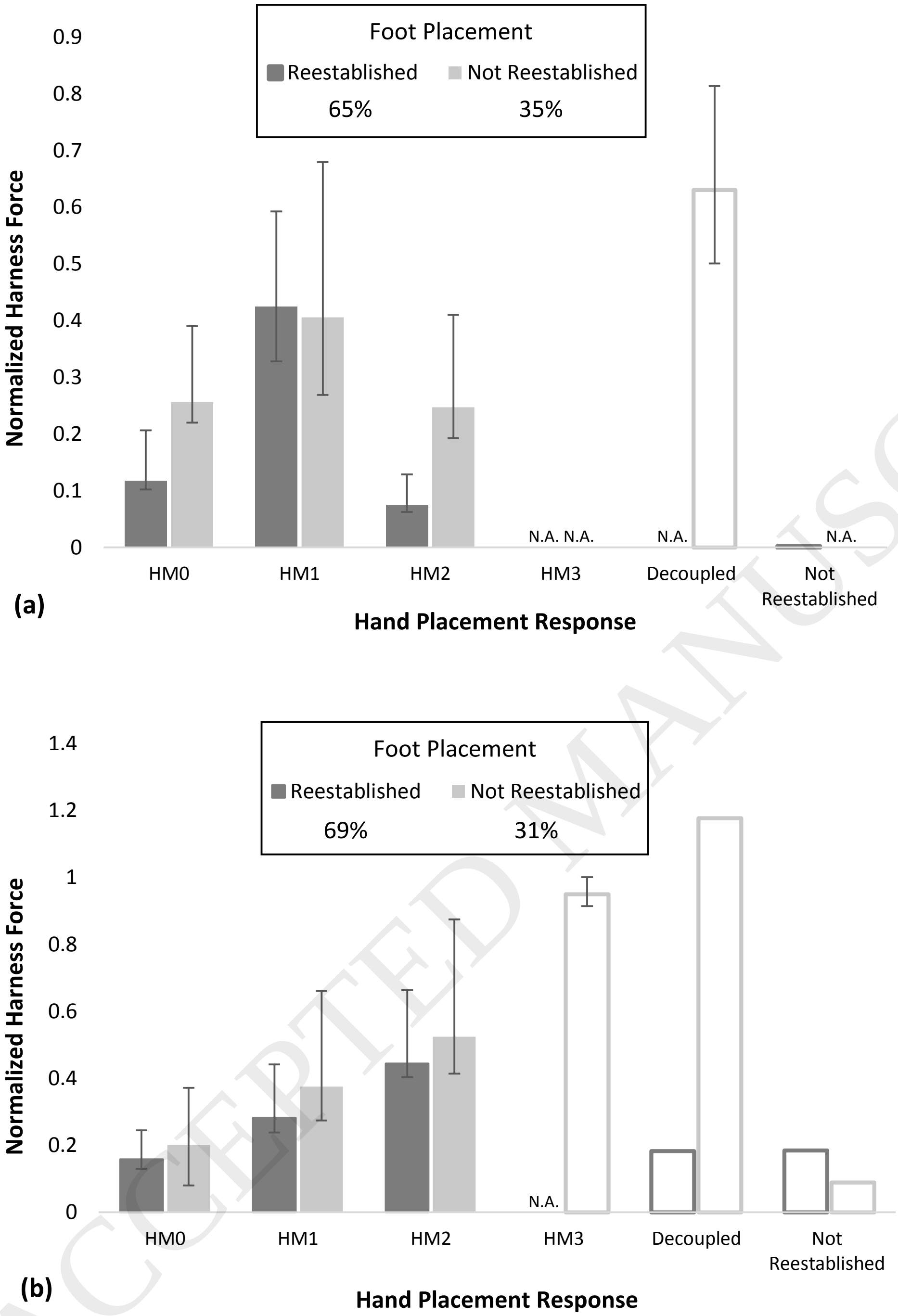
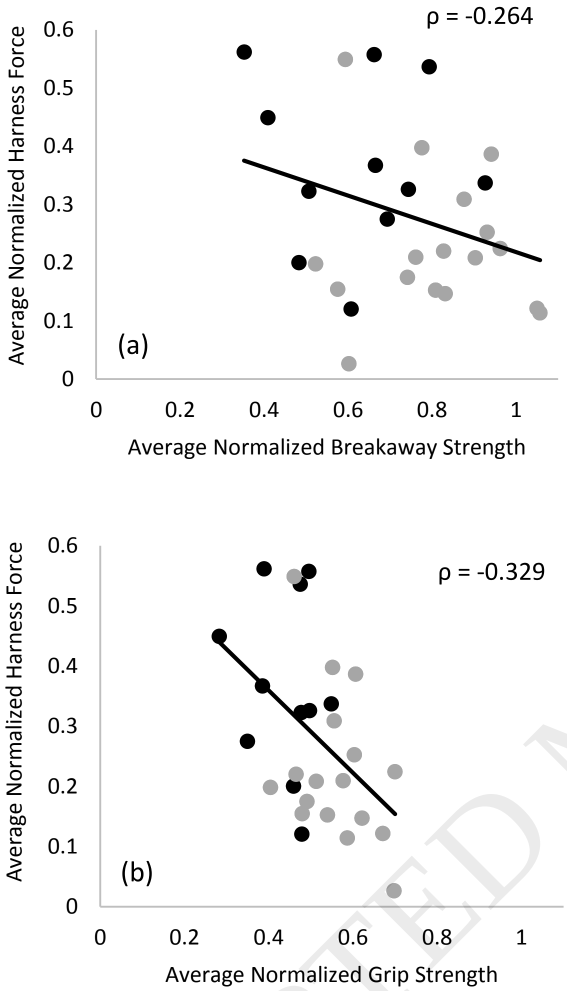

Foot Placement
Reestablished 65%
Not Reestablished 35%
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Normalized Harness Force
N.A. N.A.
N.A.
N.A.
HM0
HM1
HM2
HM3
Decoupled
Not Reestablished
(a)
Hand Placement Response
Foot Placement
Reestablished 69%
Not Reestablished 31%
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Normalized Harness Force
N.A.
HM0
HM1
HM2
HM3
Decoupled
Not Reestablished
(b)
Hand Placement Response

Figure 4


ρ = -0.264
Average Normalized Harness Force
0.6
0.5
0.4
0.3
0.2
0.1
0
(a)
0
0.2
0.4
0.6
0.8
1
Average Normalized Breakaway Strength
ρ = -0.329
Average Normalized Harness Force
0.6
0.5
0.4
0.3
0.2
0.1
0
(b)
0
0.2
0.4
0.6
0.8
1
Average Normalized Grip Strength

Table

Table 1: Results of ANOVA models with breakaway strength and grip strength (degrees of freedom, p-value, F-value). Bolded p-values are statistically significant at 5% level.

		BREAKAWAY STRENGTH		**GRIP STRENGTH**	
	df1, df2	*p-value*	*F-value*	*p-value*	*F-value*
CLIMBING DIRECTION	1, 141	**0.019**	5.689	**0.016**	5.935
HAND PLACEMENT	2, 141	**0.002**	6.519	**0.003**	5.959
FOOT PLACEMENT	1, 141	**0.019**	5.658	**0.013**	6.294
UPPER BODY STRENGTH	1, 141	**0.020**	6.049	**<0.001**	16.504
CLIMBING DIRECTION X HAND PLACEMENT	2, 141	**<0.001**	13.930	**<0.001**	17.286
CLIMBING DIRECTION X FOOT PLACEMENT	1, 135	0.112	2.561	0.086	2.992
CLIMBING DIRECTION X UPPER BODY STRENGTH	1, 135	0.615	0.254	0.800	0.065
HAND PLACEMENT X FOOT PLACEMENT	2, 135	0.941	0.061	0.729	0.316
HAND PLACEMENT X UPPER BODY STRENGTH	2, 135	0.718	0.332	0.724	0.323
FOOT PLACEMENT X UPPER BODY STRENGTH	1, 135	0.473	0.519	0.076	3.202