Effects of Gloves and Pulling Task on Achievable Downward Pull Forces on a Rung

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Objective: We examined the impacts of pulling task (breakaway and pull-down tasks at different postures), glove use, and their interaction on achievable downward pull forces from a ladder rung.

Background: Posture, glove use, and the type of pulling task are known to affect the achievable forces. However, a gap in the literature exists regarding how these factors affect achievable downward pulling forces, which are relevant to recovery from a perturbation during ladder climbing.

Methods: Forty subjects completed four downward pulling tasks (breakaway force; pull force at maximum height, shoulder height, and a middle height), using three glove conditions with varying coefficient of friction (COF) levels (cotton glove, low COF; bare hand, moderate COF; and latex-coated glove, high COF) with their dominant and nondominant hand. The outcome variable was the maximum force normalized to body weight.

Results: The highest forces were observed for the highest hand postures (breakaway and maximum height). Increased COF led to higher forces and had a larger effect on breakaway force than the other tasks. The dominant hand was associated with higher forces than the nondominant hand. Male subjects generated greater forces than female subjects, particularly for higher hand positions.

Conclusion: This study suggests that a higher hand position on the ladder, while avoiding low-friction gloves, may be effective for improving recovery from ladder perturbations.

Application: This study may guide preferred climbing strategies (particularly those that lead to a higher hand position) for improving recovery from a perturbation during ladder climbing.

Keywords: hand forces, pull strength, falls, ladder climbing, biomechanics

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INTRODUCTION

The interaction between the hand and an object is a critically important aspect of ergonomics. The hand is critical to many basic occupational tasks, including lifting and handling objects (Freivalds, Chaffin, Garg, & Lee, 1984; Garg, Hegmann, & Kapellusch, 2005), pushing or pulling (Chaffin, Andres, & Garg, 1983; Fransson & Winkel, 1991; Snook & Ciriello, 1991), and supporting balance during stair negotiation (Dusenberry, Simpson, & DelloRusso, 2009; Maki et al., 2008) and ladder climbing (Hur, Motawar, & Seo, 2012; Young, Woolley, Armstrong, & Ashton-Miller, 2009). An understanding of the ergonomic and individual factors that influence hand–object interaction is important to guiding safe workplaces.

An emerging application for research on hand–object interactions is falling from ladders. Falls from ladders are frequently initiated by a slip or misstep and account for 40% to 50% of ladder fall injuries in occupational settings (López, Ritzel, González, & Alcántara, 2011; Smith et al., 2006). Recent research has found that slips from ladders occur at the moment when the foot contralateral to the slip is in motion and that the hand or hands are commonly the only contact point after a slip (Schnorenberg, Campbell-Kyureghyan, & Beschorner, 2015). Furthermore, the hand in motion reestablishes itself with the ladder before the feet in cases where one hand is moving during slipping (Schnorenberg et al., 2015). Hand forces have been shown to support the body weight (by pulling down on the rung) and balance the body (by pulling backward or toward the body on the rung) during ladder climbing (Armstrong, Young, Woolley, Ashton-Miller, & Kim, 2009; Bloswick & Chaffin, 1990). Thus, the hands are likely an important component of the postural response to a perturbation during ladder climbing.

An incongruence currently exists between the upper-body postures that are used to assess hand–rung interactions and the upper-body postures that occur during climbing. Researchers who have examined the kinematics of unperturbed ladder climbing suggest that the average shoulder angle is 39° of flexion and the average elbow angle is 24° of flexion (Armstrong et al., 2008). However, studies on the maximum achievable forces tend to use different postures. For example, breakaway force protocols have applied approximate postures of shoulder flexion of 160° and elbow flexion of 10° while the rung was pulled vertically up away from the hand (Hur et al., 2012; Young et al., 2009). In another study that quantified hand–rung force production, the shoulder was flexed at 90° and the elbow was extended during grip force measurement (Barnett & Poczynck, 2000).

One possible reason for the incongruence in the upper-limb postures between the breakaway force protocol and ladder-climbing kinematics may be based on the assumed change in upper-body posture that occurs after a climbing perturbation. After a perturbation, the hips accelerate downward leading to a downward vertical velocity (Pliner, Seo, & Beschorner, 2017). The overall drop in hip placement, while the hands maintain their position on a rung, presumably will elevate the hand position relative to the body and likely cause an increase in shoulder flexion and elbow extension. The peak force generated by the hands once the hand reaches its maximum height (i.e., the breakaway force) may be the last line of defense before the hands decouple from the rung and the person falls to the ground, which is the underlying rationale for testing breakaway forces (Young et al., 2009). However, successful recovery from a perturbation is often accomplished by an early upper-limb response that generates forces on the rungs while the feet are reestablished back on the ladder (Schnorenberg et al., 2015). This early response may occur prior to a large increase in shoulder flexion and elbow extension. Thus, additional information is needed to understand how breakaway forces compare to the forces during a volitional pull-down task and how these volitional forces change across the multiple arm postures that might occur after a climbing perturbation.

The impact of upper-limb posture on achievable forces has been demonstrated as a critical factor in other pushing and pulling studies, indicating that it is an important consideration. Chaffin et al. (1983) found that the pulling force on a cart incrementally decreased as the height of the handle was increased. Increasing the height of a handle from 1.0 m to 1.75 m led to reductions in pushing forces between 15% and 55% depending on the handle type (Chaffin et al., 1983). Authors of another study examined the impacts of elbow and shoulder posture on the maximum weight that could be held or lifted and held (Garg et al., 2005). This study showed that force decreased with a greater shoulder flexion angle and when the lifted object was held farther away from the body (Garg et al., 2005). However, a paucity of data exists in the literature regarding the impacts of arm postures on achievable downward pull forces, related to recovery from a perturbation during ladder climbing.

Recent research has assessed the impacts of glove use and friction on achievable hand–rung forces. These studies have demonstrated that higher-friction gloves (Hur et al., 2012) or rungs (Young et al., 2009) lead to increases in the forces generated during breakaway. However, it is not clear whether the impacts of glove use or friction are generalizable for all downward pulling tasks and postures.

The purpose of this study was to examine the impacts of downward pulling task types (breakaway and volitional pull-down task at different upper-limb postures), glove use, and their interaction on achievable downward pull forces from a ladder rung.

METHOD

Forty subjects between the ages of 18 and 35 years were recruited to participate in the study (Table 1). The study consisted of two visits: The first visit tested subjects' pull forces, and the second tested their biomechanical response to ladder perturbations (Pliner et al., 2017). Only data from the first visit are reported in the present study. To be eligible for the study, subjects needed to report that they were free from musculoskeletal or neurological injuries or disorders, had a body mass of less than 114

TABLE 1: Average Age, Height, Weight, Hand Length, and Hand Width and Number of Right-/Left-Hand Dominance

Subjects	Age (years)	Height (m)	Weight (kg)	Hand Length (mm)	Hand Width (mm)	Right/Left Dominant
Males (n = 25)	23.9 (4.7)	1.8 (0.1)	80.3 (8.3)	193.5 (8.2)	90.0 (4.2)	20[a]/5
Females (n = 15)	26.1 (5.9)	1.7 (0.1)	65.3 (14.0)	173.5 (10.7)	80.7 (2.9)	14/1
All (N = 40)	24.7 (5.2)	1.8 (0.1)	74.7 (12.9)	186.9 (12.4)	86.5 (5.9)	34[a]/6

Note. Standard deviations shown in parentheses.
[a]One male was ambidextrous and was treated as right dominant in the analyses.

kg, and had a body mass index of less than 30. Also, female subjects who were or thought that they could be pregnant were excluded from the study. This research complied with the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board at University of Wisconsin–Milwaukee. Informed consent was obtained from each participant.

Prior to measuring pull forces in the first visit, subjects' height, weight, hand length (measured from the middle fingertip to the first crease of the wrist), hand width (measured from the second knuckle to the fifth knuckle), and self-reported hand dominance were recorded. Subjects then performed four different maximal exertion tests (Figures 1A and 1B), which were repeated two times for both hands and across three different glove conditions (4 tests × 2 trials × 2 hands × 3 gloves = 48 trials per subject). The four exertion tests included breakaway force and maximal pull forces at three different heights. For the pull tasks, three upper-limb posture conditions were tested: full height, where the rung was vertically placed/positioned at the maximum overhead height that a subject could reach; shoulder height, where the rung was vertically placed at the shoulder height; and a middle height, where the rung was vertically placed halfway between shoulder and full height (Figure 1B). The rung was aluminum with a circular cross-section (diameter of 38 mm) that was restricted from rotating. This rung size is typical since the Occupational Safety and Health Administration required metal rungs with a minimum diameter of 19.1 mm and wood rungs with a minimum diameter of 28.6 mm (Galassi, 2014) until 2017.

The three glove conditions included a cotton glove, a latex-coated glove, and a bare-handed (i.e., no glove) condition (Pliner et al., 2017) and were intended to achieve varying levels of friction (Figure 1C). The cotton gloves were intended to have a lower coefficient of friction (COF) compared with bare hand (Seo, Armstrong, & Young, 2010), and the latex gloves were intended to have a higher COF compared with bare hand (Hur et al., 2012), when contacting an aluminum surface. Three sizes of each set of gloves were bought off of the shelf to accommodate different hand sizes. The latex-coated gloves were made of knitted fabric with a latex palm (HD30503/L3P, West Chester, Inc., Monroe, OH), and the cotton gloves were made of 100% cotton (COTPR, Drillcomp, Inc., New Hope, PA). The thicknesses of the gloves on the palmar side were 1.57 mm and 0.31 mm for the latex and cotton gloves, respectively. For the breakaway trials, subjects were asked to hang on to the rung as long as possible while the rung was moved up by a motor over a period of approximately 5 s in the same manner as in Hur et al. (2012). In the maximum-pull trials, subjects were asked to pull the stationary rung downward as hard as possible for 5 s. Subjects received verbal encouragement during the maximum-pull-force trials. A restricted randomization scheme was utilized to ensure that all subjects completed exactly two trials for each experimental condition but in a completely random order.

The apparatus for measuring breakaway and maximal pull force consisted of a seat and straps to prevent the subject from being lifted off of the seat during breakaway, a circular rung that was attached to a cable system, a load cell (sampling at 1 kHz) that was attached to the cable to measure pull force, and a winch that retracted the cable to force a decoupling between the hand

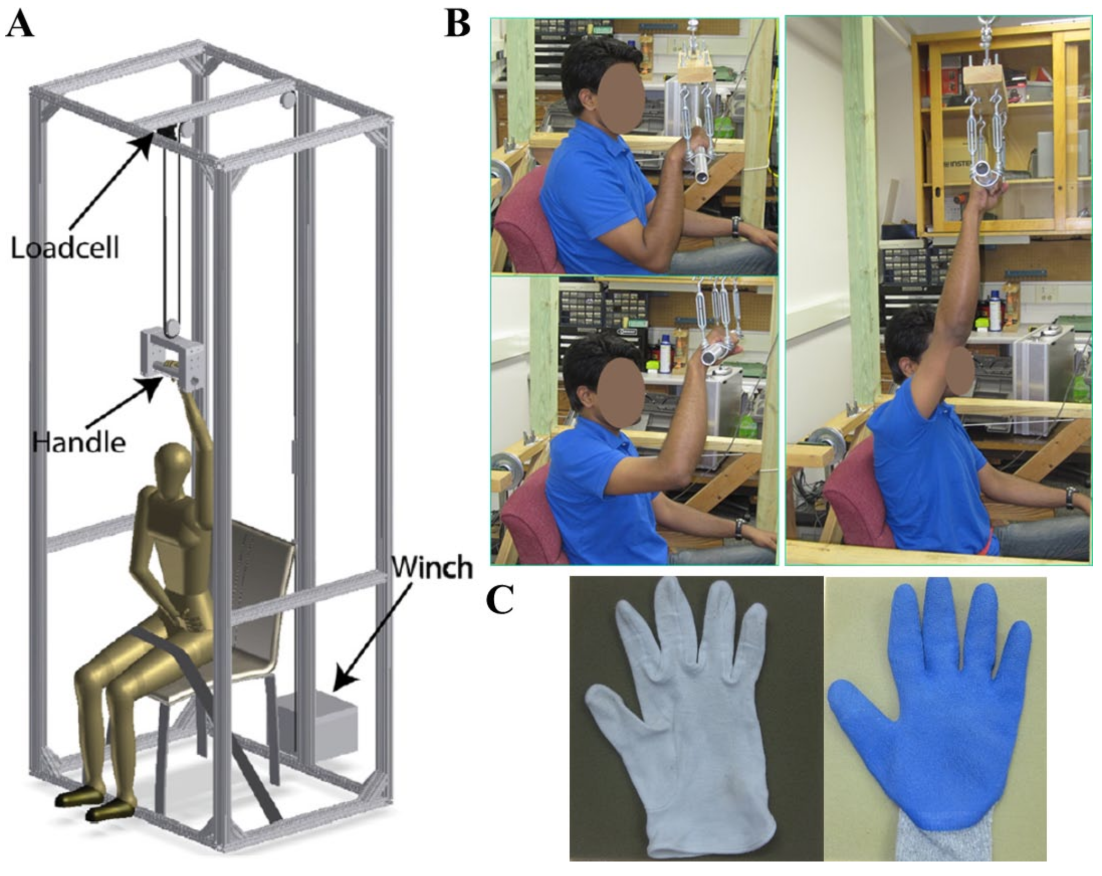

Figure 1. (A) Diagram of the testing apparatus. (B) The three postures included in this study: shoulder height (upper left), medium height (lower left), and full height (right). (C) The two glove designs used in this study: cotton (left) and latex (right). Figure 1A from "Hand Breakaway Strength Model: Effects of Glove Use and Handle Shapes on a Person's Hand Strength to Hold Onto Handles to Prevent Fall From Elevation," by P. Hur, B. Motawar, and N. J. Seo, 2012, *Journal of Biomechanics, 45*, p. 960. Copyright 2012 by Elsevier. Reprinted with permission.

and rung during the breakaway tests (Hur et al., 2012). The anterior-posterior position of the rung was set so that a person of average stature would have his or her shoulder flexed at 160° and elbow flexed at 10° during the breakaway trial, consistent with previous research (Hur et al., 2012).

Data and Statistical Analysis

The peak force from the load cell was recorded from each trial, and the two trials for a given condition were averaged. Forces were normalized to body weight (i.e., presented as the proportion of force to the subject's body weight) because preliminary analyses revealed that applied forces were positively correlated with body weight. A split-plot ANOVA was used with peak force as the dependent variable. The ANOVA included the following within-subject independent variables: task type (breakaway, full-height pull, medium-height pull, or shoulder-height pull), glove condition, and hand (dominant versus nondominant). Gender was a between-subject independent variable. All first-order interactions were also included in the model. When a statistically significant interaction was present, post hoc Tukey honest significant difference was performed across all permutations of the two interacting variables. Then, statistical differences across one variable

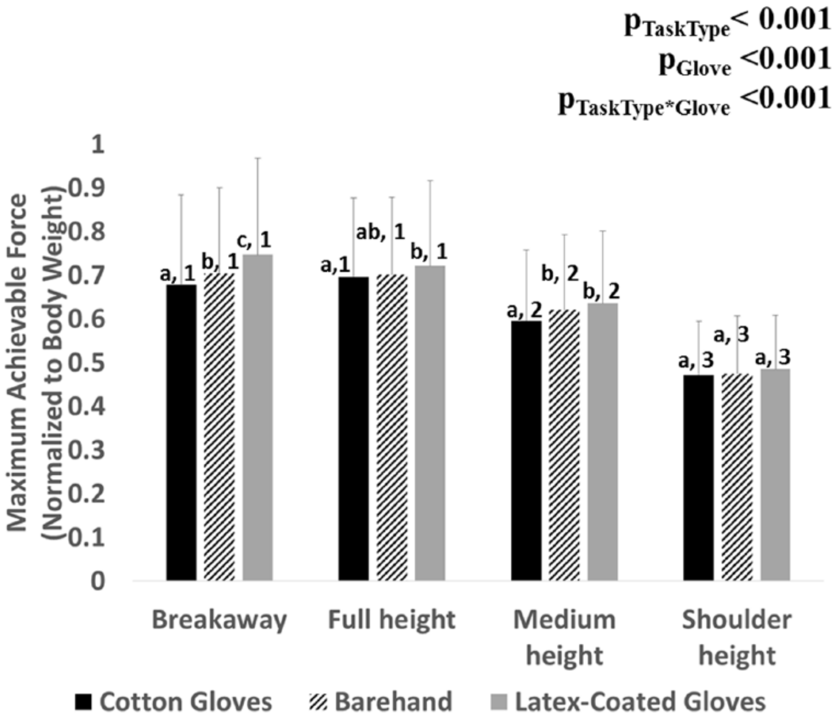

Figure 2. Impact of task and glove condition on the maximum achievable force. Error bars represent standard deviation. Numbers are used to indicate statistical significance across task type for each glove condition. Task types with the same number are not significantly different within a glove condition. Letters are used to indicate statistical significance across gloves for each task type. Gloves that have the same letter are not significantly different within a given task. Results are averaged across the two hands.

were reported for each level of the other variable. For example, differences across glove conditions would be reported for each level of task type, and differences across task types would be reported for each level of glove condition if a significant Task Type × Glove Condition interaction was observed. A significance level of 0.05 was used for all analyses.

RESULTS

The average peak hand force normalized to body weight across all conditions was 0.63 (*SD* = 0.19). Significant effects were observed for task type, $p < .001$, $F(3, 114) = 60.6$; glove condition, $p < .001$, $F(2, 76) = 24.3$; hand, $p < .001$, $F(1, 39) = 53.5$; gender, $p < .001$, $F(1, 38) = 15.7$; the interaction between task type and glove condition, $p < .001$, $F(6, 669) = 5.2$; and the interaction between task type and gender, $p = .006$, $F(3, 114) = 4.4$. The interaction between task type and hand, $p = .081$, $F(3, 669) = 2.3$; the interaction between glove condition and hand, $p = .889$, $F(2, 669) = 0.1$; the interaction between gender and hand, $p = .908$, $F(1, 38) = 0.0$; and the interaction between gender and glove, $p = .090$, $F(2, 76) = 2.5$, were not significant.

For each glove condition, larger forces were observed for breakaway and full-height pulling, followed by medium-height and then shoulder-height pulling (Figure 2). The maximum achievable force for the breakaway test was significantly different across each of the three gloves, whereas the force at the shoulder height was not influenced by the glove condition (Figure 2). For the full-height task, the cotton glove led to lower forces than the latex-coated glove

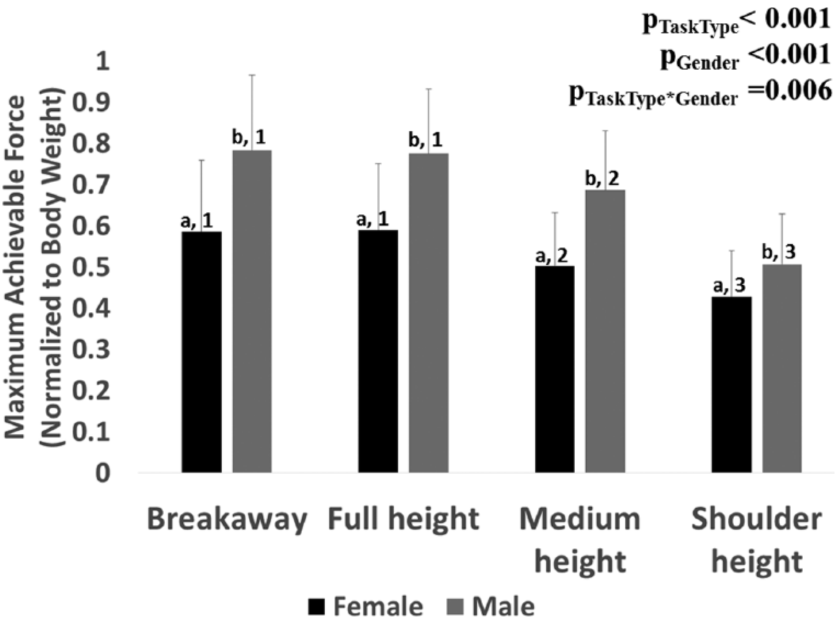

Figure 3. The effect of gender and its interaction with task type on the peak force that was generated. Forces are averaged across hand and glove conditions. Error bars represent standard deviation. Numbers are used to indicate statistical significance across task type for each gender. Task types with the same number are not significantly different within a gender. Letters are used to indicate statistical significance across gender for each task type. Different letters indicate a difference in generated force across genders within a given task.

(Figure 2), whereas no difference was observed between bare-hand condition and latex-coated glove condition or the bare-hand condition and the cotton glove condition (Figure 2). For the medium-height task, the cotton glove led to lower forces than the bare-hand and latex-coated glove conditions, but no difference was observed between bare-hand and latex-coated glove conditions.

For both genders, larger forces were observed for breakaway and full-height pulling, followed by medium-height pulling and then shoulder-height pulling (Figure 3). Males generated greater forces than females for each of the four tasks. The achievable force gap between genders was smaller for the shoulder-height pulling task (difference of 0.08 between genders) compared with the other tasks (difference of 0.18 to 0.20 between genders) (Figure 3). The dominant hand (M = 0.64, SD = 0.20) generated greater force than the nondominant hand (M = 0.61, SD = 0.19) (Figure 4).

DISCUSSION

This study showed that pull height has a substantial impact on the force that can be generated and on the relationship between gloves and hand–rung force. Specifically, this study determined that the downward force that can be generated increases as the hand is moved farther overhead. Gloves had the biggest impact on force production in the breakaway condition and the lowest impact at shoulder height, suggesting that friction may have been a limiting factor during breakaway tasks but not at lower pull heights. This study suggests that a hand that is placed higher on a ladder relative to the body may be more capable of generating forces that can arrest a fall.

The results of this study are generally consistent with previous research that has examined the impacts of gloves, gender, and arm position on achievable forces. The latex-coated glove led to increased breakaway forces relative to the

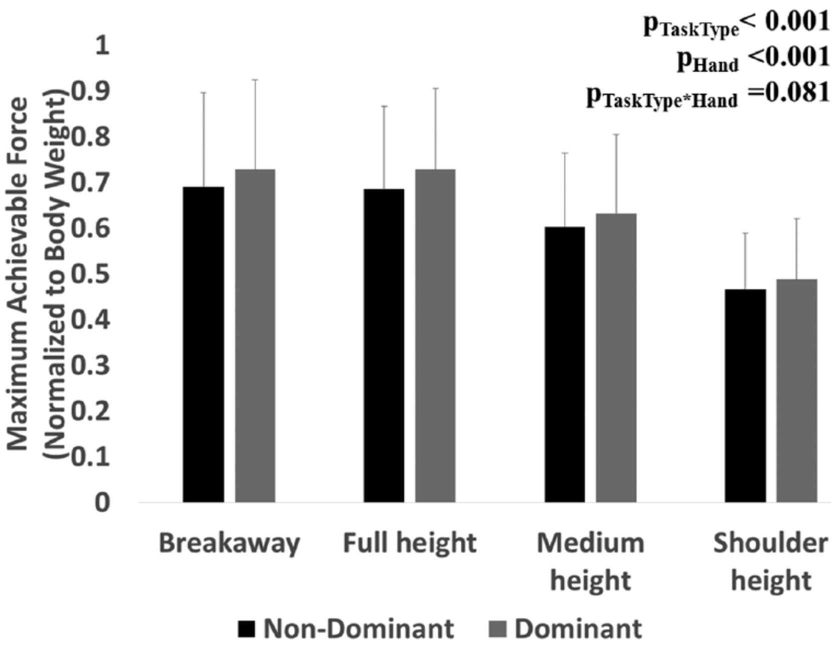

Figure 4. Impact of hand dominance and task type on the peak force that was generated. Forces are averaged across glove conditions.

bare-handed condition, and the lower friction glove led to reduced breakaway forces (Figure 2), consistent with Hur et al. (2012). Male subjects generated greater forces than female subjects even when the force was normalized by their body weight, consistent with previous research (Young, 2011; Young et al., 2009). The magnitude of breakaway force values were consistent with Hur et al. but smaller than those reported by Young et al. (2009). This discrepancy may be explained by the attachment of the rung, which was not fixed in the forward/backward direction in the present study. In Young et al. (2009), the rung was fixed in the forward/backward direction, which affords greater stability and greater force exertion (Seo & Armstrong, 2009). Furthermore, arm posture influenced the amount of force that could be generated, consistent with several previous studies (Chaffin et al., 1983; Fothergill, Grieve, & Pheasant, 1992; Garg et al., 2005; Parvatikar & Mukkannavar, 2009; Su, Lin, Chien, Cheng, & Sung, 1994). Interestingly, the effect of upper-limb posture on force generation of the present study was opposite of the effects observed with lifting (Garg et al., 2005) or pushing/pulling studies (Chaffin et al., 1983; Fothergill et al., 1992) that have shown a reduced ability to generate force with higher hand position. Therefore, it seems clear that the impact of posture on force generation is dependent on the direction that the force is being applied.

The increase in pull force generation with a higher hand position may be explained by the tension–length relationship of the back muscles. Previous research has found that the latissimus dorsi muscles have a high level of activation when resisting a sudden upward force on the hand by a ladder rung in this posture (Hur, Motawar, & Seo, 2014). This muscle group is thought to generate the downward pull force by depressing the scapula (Richardson, 2011). Grasping at a higher location likely leads to an elevation of the scapula, thus lengthening the latissimus dorsi muscle group and increasing the tension in this muscle. Therefore, the length–tension relationship in this muscle may explain the greater force generation capacity at higher heights.

The biomechanical reason for the impact of glove and its interaction with posture on pulling force may be explained by friction and its role as a limiting factor during pulling. Previous research and hand models have demonstrated that friction forces between a hand and object can increase the overall force that is applied to that object (Hur et al., 2012; Young et al., 2009). However, these friction forces may be relevant only when the force between the hand and object is the limiting factor. As previously described by Young et al. (2009), the force generated between a hand and rung is dependent on a series of segments (torso, arms), and the overall pull force is limited by the weakest segment. Given that gloves had the largest impact on pull force in the breakaway condition and no significant effect on pull force in the shoulder-height pull condition, it seems likely that the grip force was the limiting factor in breakaway testing but that the torso and shoulder strength limited force generation when pulling down from shoulder height. Grip force as a limiting factor during breakaway is supported by previous research (Hur et al., 2012; Young et al., 2009), and torso/shoulder strength being limited at shoulder height is supported by the fact that the latissimus dorsi is shortened when the humerus is in a lower position and the biceps brachii are shortened when the elbow is in flexion (Richardson, 2011). Thus, a biomechanical basis exists to explain the combined effects of posture and grip strength.

The results of this study have significant ramifications for guiding safe climbing and perturbation recovery processes. This study suggests that climbers are able to produce greater forces if the hands are extended higher relative to the body. Therefore, achieving a coordination pattern to make sure that the hands are moved to a higher rung before the feet are moved to a higher rung may be beneficial during ascent, whereas moving the hands after moving the feet may be beneficial during descent of the ladder. Training ladder users to climb with a four-beat (limbs moving on separate time intervals) temporal climbing pattern for ascent and a two-beat (one hand and one foot moving within the same time interval) temporal climbing pattern for descent may achieve these preferred coordination patterns. Previous literature displaying the temporal climbing patterns on a ladder show that the hand leads the foot during four-beat and that the foot leads the hand during two-beat climbing patterns (Hammer & Schmalz, 1992; McIntyre, 1983). In addition, these patterns vary between climbs and within climbs (Hammer & Schmalz, 1992; McIntyre, 1983), indicating that most ladder climbers are capable of performing both techniques. Future intervention studies would have to be performed to determine whether this type of training is feasible for ladder climbers, especially under different glove conditions. Also, the finding that gloves had a diminished contribution in shoulder-height pull force trials compared with breakaway trials suggests that gloves may not offer many benefits during the initial recovery response period, when the hands are attempting to arrest the fall, consistent with previous findings (Pliner et al., 2017). However, high-friction gloves may still play an important role in later stages of the recovery process, when the momentum of a downward fall creates the risk of the hand decoupling from the ladder.

A few important limitations should be acknowledged in the study. First, just one rung cross-section and orientation was utilized. Previous studies have noted that the relationship between hand position and maximum achievable force can be modulated by the design of the handles (Fothergill et al., 1992). Second, the experimental apparatus in this study measures only the interaction between the hand and rung, which does not consider the many biomechanical complexities that occur during an actual ladder fall event. Thus, additional research is needed to quantify the dependence of fall recovery on achievable downward pull forces. Last, the force values were normalized to body weight based on preliminary information that force was proportional to body weight. This relationship may not apply to high-weight individuals. Therefore, the results of this study may not apply to these individuals.

This study established that the achievable downward hand force increases with higher hand positioning. The biomechanical mechanism that explains the role of posture on pull force is the length–tension relationship in the proximal muscles, like the biceps brachii and the latissimus dorsi. This study indicates that climbing styles whereby a hand is extended farther overhead may be beneficial to fall recovery (e.g., the four-beat style during ascent or the two-beat style during descent).

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KEY POINTS

- Subjects performed breakaway tests and three pulling tasks at different upper-limb postures while wearing three gloves with varying friction.
- Achievable forces were highest when the arm was at its highest position.
- High-friction gloves increased achievable forces and had the greatest effect for the breakaway task.
- A higher hand position may improve recovery from a perturbation during ladder climbing.

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