Published in final edited form as:

Appl Ergon. 2022 February ; 99: 103639. doi:10.1016/j.apergo.2021.103639.

Selected movement and force pattern differences in rail- and rung-climbing of fire apparatus aerial ladders at 52.5° slope

Qianyi Albert Fu[a,*], **Peter Simeonov**[b], **Hongwei Hsiao**[b], **Charles Woolley**[a], **Thomas J. Armstrong**[a]

[a]Center for Ergonomics, University of Michigan, Ann Arbor, MI, USA

[b]Division of Safety Research, National Institute for Occupational Safety and Health, Morgantown, WV, USA

Abstract

This study compares human climbing performance, including climbing speed and movement and force patterns, between rail- and rung-climbing styles for a moderate aerial ladder slope (52.5°). Hand and foot movements and forces were recorded for 9 male and 10 female firefighters as they ascended and descended a 3.4-m ladder using elevated handrails (rail-climbing) or rungs (rung-climbing) for hand support. The results indicated that climbers used three or more points of contact 54% of the time for rung-climbing and 100% of the time for rail-climbing. Furthermore, rail-climbing was 10% faster than rung-climbing. In rail-climbing, the lateral hand forces were mostly directed away from the body; while during rung-climbing, they were alternated in lateral and medial directions. Overall, the results suggested that rail-climbing provides better control over body positioning and faster climbing speed. Furthermore, the continuous contact of both hands in rail-climbing may reduce the fall risk by facilitating the recovery from a slip or perturbation.

Keywords

Aerial ladder; Hand support; Climbing speed; Points of contact

1. Introduction

Ladders are widely used and are a common cause of injuries. Jobs that involve ladder climbing include painting, construction, roofing, communication tower maintenance, and firefighting. Firefighting is of special interest in this study because ladder-climbing during firefighting is physically demanding, hazardous, and involves ladder configurations with a

*Corresponding author. qifu@umich.edu (Q.A. Fu).

Disclaimer

The findings and conclusions in this article are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC), or the University of Michigan. Mention of any company or product does not imply endorsement by NIOSH, CDC, or the University of Michigan.

Joon Oh Seo assisted with data collection and reduction, Daniel Adsit assisted with data analysis, and Tsui-Ying Kau assisted with statistical analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

broad range of slopes (Fig. 1a). Ladder configurations and climbing styles affect climbing speed, biomechanical loads, and fatigue (Guidotti, 1992) and may ultimately affect the climber's fall risk. In 2011, work-related ladder falls resulted in about 34,000 non-fatal injuries treated in U.S. emergency departments and 113 fatalities (Socias et al., 2014).

Biomechanical loads have been studied for vertical and steep-sloped ladders (Bloswick and Chaffin, 1990; Armstrong et al., 2009; Martin et al., 2020) but not for ladders sloped at more moderate angles (i.e., 52.5°) that are frequently used by firefighters. Aerial ladders can be extended to as much as 30 m; they are generally used at slopes from 30° to 75° (National Fire Protection Association, 2008). Ascending and descending these ladders in firefighter gear is very physically demanding, especially at the slope of 75° (Vi, 2008; Barron et al., 2018). The arms and hands are used to help support, lift, and lower the body weight from one rung to the next (Armstrong et al., 2009). The arms and hands are also important if a foot slips from a rung while climbing (Schnorenberg et al., 2015). Even though on a moderately sloped aerial ladder a climber tends to fall into the ladder, quick use of the hands is required to re-establish control of the body with respect to the ladder and prevent sliding down or off the ladder (Pliner et al., 2019). Simeonov et al. (2020) previously provided a detailed description of the climbing behavior study methods and results of biomechanical findings. In that study, 9 slips were observed in 3040 ladder ascents and descents by 19 firefighters. The current study examines differences in climbing behavior during rung-climbing and rail-climbing at the moderate aerial ladder slope of 52.5° where climbers may choose to use rungs or elevated handrails for hand support.

McIntyre (1983) classified climbing patterns both spatially as lateral (arm and leg moving on the same side of the body) and diagonal (arm and leg moving on different sides of the body) climbing and also temporally as 2-beat (arm and leg moving at the same time) and 4-beat (arm and leg moving at different times). Pliner and Beschorner (2017) found that the climbing patterns did not significantly affect the fall severity; however, the 2-beat pattern resulted in a brief period during each climb cycle in which the climber was supported by only two-point of contact with the ladder (Dewar, 1977; Hammer and Schmalz, 1992; Jensen and Holland, 2020). Climber's posture during a two-point contact period is inherently unstable. A quick response would be required to re-establish control over the position of the body with respect to the ladder where a foot or a hand slips during these periods. It has been argued that climbing with rungs has faster muscle activation patterns in the case of slips (Schnorenberg et al., 2015) and facilitates effective grasp to arrest a fall (Barnett and Poczynck, 2000); however, rail-climbing may offer an advantage over rung-climbing in that both hands can be slid along the rail. The hand's proximity to the rail puts it in a position to quickly stabilize the body should there be a sudden loss of balance. Also, rung-climbing could require additional time to reach for and grasp a rung to regain control.

Armstrong et al. (2009) showed that greater lateral hand forces, but lower resultant hand forces were exerted on the rails at the sides of the ladder than on the rungs near the center of the ladder for vertical ladder climbing at 80° and 90°. Researchers have expressed concerns that forces in the medial-lateral direction might be destabilizing. In addition, it has been argued that rung-climbing provides greater ability to hold onto the ladder, maintain control, and recover from fall than rail-climbing if the feet slip (Schnorenberg et al., 2015; Young et al., 2009). This is particularly important for climbing vertical or near-vertical ladders in which the climber falls away from the ladder and rapid-forceful exertions are required as opposed to climbing on ladders at lower slopes (Szychlinska et al., 2017; Young et al., 2009).

This paper examines a subset of data from a study of climbing behavior by firefighters ascending and descending aerial ladders at slopes from 30° to 75° (Simeonov et al., 2020). This work aimed to examine how climbing speed and how hand and foot movement and force patterns are influenced by using elevated handrails versus rungs for hand support while climbing at 52.5°. In addition to points of contact and hand forces, climbing speed and the distance between hands and feet are of interest. Self-selected speed has been used as the main performance measure and can imply the easiness and comfort of climbing the ladder (Lee et al., 1994; Song et al., 2020). The distance between hands and feet during climbing can be used to test the hypothesis that rung climbing restricted the possible location of hand placement.

2. Methods

Simeonov et al. (2020) provided a detailed description of this study with results about the biomechanical aspects. The study included the recruitment and testing of 10 male and 10 female firefighters. Due to missing force data for 1 male participant, this paper only included data from 9 male and 10 female firefighters. The mean of female participants' age was 32.8 ± 10.4 years, height 167.7 ± 5.1 cm, weight 74.2 ± 13.7 kg. The mean of male participants' age was 35.6 ± 12.0 years, height 175.0 ± 7.3 cm, weight 82.8 ± 14.4 kg. Participants were informed of the study goals and procedures and signed a written consent in advance of data collection. The study protocol was approved by the Institutional Review Boards of the University of Michigan and the National Institute for Occupational Safety and Health.

The study used a specially constructed and instrumented 3.4-m-long ladder with adjustable geometry. The data for climbing the ladder at 52.5° slope with 305 mm elevated cylinder-shaped hand-rails and rung spacing at 305 and 356 mm (as shown in Fig. 1b) was analyzed in this paper since it allowed comparing climbing using rails or rungs as support. The experimental settings are within the range of the aerial ladder standard (NFPA 1901: Ch. 19, 2003 Edition, 2008). The ladder rails and rungs were attached to three-axis force gauges to record hand and foot forces at 100 Hz, and NDI Optotrak Certus (NDI Waterloo, Ontario, Canada) was used to track hand and foot movements at 100 Hz. A climber performing rail- and rung-climbing at 52.5° slope on this ladder is shown in Fig. 1c and 1d.

Participants climbed up and down a ladder eight times one foot per rung with a 5-s break at the top and bottom for balanced combinations of the experimental conditions (305 or 356 mm rung spacing, ascending or descending, and rung or rail hand-hold). The participants were instructed to climb with their comfortable pace and patterns (lateral or diagonal, and 2 or 4-beat) and with their work boots and gloves. Female participants wore a 10.5 kg backpack and males wore an 11.9 kg backpack to simulate gear that would be normally carried to fight a fire (Hsiao, 2014). Participants practiced climbing in advance of each trial to establish a normal pace for that trial. All participants had formal ladder-climbing training and ladder climbing experience.

Key hand and foot movement and force parameters were extracted from the movement and force data. To keep measurements consistent, all parameters were calculated for each single climb cycle under each trial. For example, the time from when the left foot reaches the 2nd rung to when the left foot reaches the 4th rung was considered as the duration of one climb cycle, in which both feet had their swing and stance phases. Because the force gauges had noise and hysteresis levels of less than 1 N, the force data were processed with a threshold value of 1 N to determine the contact of hands and feet with the ladder.

Dependent variables included: 1) climbing speed, a measure of climbing easiness, comfort, and efficiency, was calculated by dividing the distance between 2 rungs by duration of one climb cycle; 2) ankle-wrist distance, a measure of optimal hand placement in terms of comfort, was calculated as the average distance between the supported hand and foot (when the hand and foot were in contact); 3) two-point contact duration, a kinematic (movement) measure of potential postural instability, was calculated by the time of 2-point contact during climb cycle; and 4) normalized peak resultant hand forces, a force measure of potential postural instability, was calculated for each climb cycle and normalized with the participant's body weight. The hand force components were calculated to demonstrate and analyze the force direction for each climb cycle.

For all dependent variables, repeated measures analyses of variance (ANOVAs) were performed using the SAS MIXED procedure (SAS Institute Inc., Cary, NC, USA) to evaluate the effect of the experimental conditions. Participants' gender, climbing direction, rung spacing, and hand support climbing style were considered as independent variables and the participant was used as a random effect. Additional correlation analysis was performed (by Minitab 18, State College, PA) to test for possible associations between participants' heights and weights and the dependent variables.

A 2 × 2 × 2 × 2 (gender, climbing direction, rung spacing, and hand-hold style) ANOVA was performed for all dependent variables with the second-order interactions. Paired *t*-tests were performed to determine the significant differences due to the effect of the interaction terms.

3. Results

The results from the ANOVA are shown in Table 1 for 8 climb cycles from each participant under each trial for each climbing direction. The ANOVA demonstrated significant effects ($p < 0.05$) of hand-hold style on climbing speed, ankle-wrist distance, and duration of two-point contact. There were also significant interactions of hand-hold style and climbing direction for two-point contact duration and normalized resultant peak hand force that will be presented in Sections 3.3 and 3.4. The statistical values from ANOVA are presented in *p*-value with the associated *F*-value, and the statistical values from paired *t*-tests are presented only with the *p*-value in this section.

3.1. Climbing speed

The ANOVA demonstrated a significant effect of hand-hold style (rung/rail) on climbing speed (Table 1). Climbing with rails was 10% faster ($F = 41.16$, $p < 0.001$) than with rungs (0.43 ± 0.06 m/s vs. 0.39 ± 0.05 m/s for ascending and descending pooled). For comparison, the climbing speed of males was 13% faster ($F = 1.02$, $p = 0.022$) than females (0.43 ± 0.06 m/s vs. 0.38 ± 0.05 m/s); climbing in ascending was 8% faster ($F = 31.47$, $p < 0.001$) than in descending (0.42 ± 0.07 m/s vs. 0.39 ± 0.04 m/s); and climbing on ladders with 305 mm rung spacing was 5% faster ($F = 14.22$, $p < 0.001$) than on ladders with 356 mm rung-spacing (0.42 ± 0.06 vs. 0.40 ± 0.05 m/s).

3.2. Ankle-wrist distance

There was a significant effect of hand-hold style (rung/rail) on ankle-wrist distance (Table 1). The ankle-wrist distance during rail-climbing was 6% smaller ($F = 13.49$, $p < 0.001$) than during rung-climbing (1254 ± 96 mm vs 1329 ±140 mm). For comparison, the ankle-wrist distance during climbing with 356 mm rung spacing was 3% smaller ($F = 4.12$, $p = 0.045$) than with 305 mm rung spacing. The correlation between ankle-wrist distances and participants' heights was significant only for rung-climbing ($r = 0.33$, $p = 0.006$) but not for rail-climbing ($r = 0.11$, $p = 0.397$).

A histogram of ankle-wrist distance distribution with rail- and rung-climbing for 305 mm and 356 mm rung spacing is shown in Fig. 2. Ankle-wrist distances for rail-climbing were continuously distributed (Fig. 2a and b). For rung-climbing, hand and feet locations were constrained to integer multiples of rung spacing, and the results appeared in clusters (Fig. 2c and d).

3.3. Two-point contact duration

The ANOVA revealed a significant effect of hand-hold style (rung/rail) on the variable two-point contact duration (Table 1 and Fig. 3). For rail-climbing, the two-point contact duration (based on the 1 N threshold) was not observed (0% ± 0%). Three- or four-point contact were maintained continuously for all trials. For rung-climbing, two-point contact duration ranged from 1% to 88% of the complete climb cycle with a mean of 46% ± 17%. In addition, the significant interaction of hand-hold style with climbing direction revealed that the two-point contact time for rung-climbing was 18% greater ($F = 6.51$, $p < 0.001$) for climbing up than climbing down (Fig. 3). A sample diagram of hand and foot contacts during rung-climbing and rail-climbing in Fig. 4a and b shows regular and frequent occurrences of two-point contact during the rung-climbing.

For rung-climbing, the two-point contact periods per climb cycle ranged from 60 ms to 760 ms with a mean and standard deviation of 210 ± 138 ms. The distribution of the duration of each two-point contact period is shown in Fig. 5. About 5% of the durations exceed 0.5 s.

3.4. Normalized peak resultant hand forces

The ANOVA showed a significant main effect of climbing direction and a significant interaction between hand-hold and climbing direction (Table 1). The significant effect of climbing direction indicated that climbing down (descending) as compared to climbing up (ascending) was associated with an increase (55.1%, $p < 0.0001$) of normalized peak resultant hand force. The significant interaction between hand-hold and climbing direction for the normalized peak resultant hand force further indicated: 1) a considerable increase of normalized peak resultant hand forces (162.5%, $p < 0.0001$) during ascending compared with during descending only for rail-climbing condition; 2) a decrease of normalized peak resultant hand forces (−45.2%, $p < 0.0001$) for rail-climbing compared with rung-climbing during ascending; and 3) an increase of normalized peak resultant hand forces (40%, $p = 0.0005$) for rail-climbing compared with rung-climbing during descending (Fig. 6).

Sample plots of 3D hand forces for rail-climbing and rung-climbing during ascending are shown in Fig. 7(a) and (b). Vertical forces were mainly exerted in inferior for both rail- and rung-climbing. Horizontal forces were first exerted in the anterior direction and then in the posterior direction for both rail- and rung-climbing. Lateral forces were exerted in the lateral direction for the rail-climbing and exerted first in the medial direction and then in the lateral direction for the rung-climbing. The sample plots showed that this participant exerted less force in the medial direction during the rung-climbing than for rail-climbing; however, the lateral force direction changed for each hand contact during the rung-climbing, from pulling the body towards the supporting hand at the beginning to pushing the body away from the supporting hand at the end of the cycle for reaching the next rung. For rung-climbing, the lateral force direction was alternated, while for rail-climbing it was consistent for both ascending and descending.

4. Discussion

The significant difference in climbing speed between rail- and rung-climbing (Table 1) implies that reaching for and grasping a rung is more complex and requires greater motor control and time than sliding the hands along the rails. Defined by Karger and Bayha (1987), in the Methods-Time Measurement (MTM), Case B Reach is “Reach for a single object in a location that may vary slightly from cycle to cycle that requires greater visual and muscular control to direct the hand”, and Case E Reach is “Reach to an indefinite location to get the hand in position for body balance, for the next motion, or out of the way”. The rails help to guide the hands to slide from one location to the next self-selected location, which can be defined as Case E Reach with low motor control. For the rung-climbing, participants must rely on some combination of memory and feedback from the visual and tactile pathways to reach for the next rung location, which can be defined as “Case B Reach” with medium motor control in MTM. In rail-climbing, relaxing and tightening the grip from one reach to the next is a simple motion that requires minimum effort, while rung-climbing requires deliberate opening and closing of the fist as the hand moves from one rung location to another.

In addition to providing coupling forces, rail-climbing provides important tactile feedback that helps the climber to detect and correct minor perturbations that can be corrected with small forces before perturbations are detected from vestibular feedback. Based on a review of 17 high-quality studies, Oates et al. (2017) concluded that haptic feedback provides an immediate reduction in variability of gait step parameters and whole-body stability, as well as a decrease in lower limb muscle activity. Previous studies show that vibrotactile feedback can be used to reduce postural sway (Sienko et al., 2013). As movement perturbations outside the range of the intended position and movement increase, so does the effort required to compensate and prevent falling. Elevated side-rails on aerial ladders enable the climber to find their preferred hand location for body support while providing continuous tactile feedback to help the climber maintain whole-body stability, thereby reducing the risk of falling.

There was a significant difference in the pattern of the ankle-wrist distance between rail- and rung-climbing (Table 1). The clustered distribution for the ankle-wrist distance reflects the constraints of hand placement during the rung-climbing. These indicate that rail-climbing grants the climber more freedom on the hand placement, and thus the climber is able to achieve a more comfortable posture during climbing. The ankle-wrist distance was significantly greater for 305 mm rung spacing than 356 mm rung spacing conditions. The 305 mm rung spacing offers distance selections of 915, 1220, and 1525 mm for the distances of 3, 4, and 5 rungs, respectively. On the other hand, the 356 rung spacing offers distance selections of 1068 and 1424 mm for the distances of 3 and 4 rungs, respectively. As shown in Fig. 2(c) and (d), the participants preferred to use the 5 rung distance (1525 mm) with 305 mm rung spacing while preferred to use the 4 rung distance (1424 mm) with 356 mm rung spacing. This resulted in the observed greater ankle-wrist distance with 305 mm rung spacing than with 356 mm rung spacing.

It can be argued that the rail-climbing may be safer than the rung-climbing because both hands are always close to the rails. It was observed that the time for each two-point contact ranged from 60 to 760 ms for rung-climbing (Fig. 5), but no two-point contact was observed for rail-climbing (Fig. 3). The foot reaching to the next rung could slip or misstep which tended to occur during two-point contact (Schnorenberg et al., 2015). Pliner et al. (2020) found that the required hand forces to recover from such an event could exceed an individual's grasping capacity, especially during descending. Also, the time required for the moving hand to reach a rung and exert peak force could be as long as 400 ms. While climbing with the rails, the proximity of the hand to the rail makes it possible for a person to quickly re-establish the coupling and regain control over the body position to prevent a fall. On the other hand, Schnorenberg et al. (2015) found that hands on rails tended to associate with slower upper-limb muscle activation onset and peak response time compared with hands on rungs. Thus, rail-climbing may be favored due to less time needed to establish coupling, while rung-climbing may be favored due to less time needed for muscle activation.

From the perspective of the breakout strength, the hand breakaway strength for a fixed horizontal cylinder (similar to rung-climbing) and a fixed vertical cylinder (similar to rail-climbing) was 668 ± 40 N and 435 ± 27 N, respectively, according to the values reported by Young et al. (2009). Thus, both hands on rails can exert greater forces than one hand on rungs to facilitate recovery. These findings have important implications for the fall risk, as there has been some debate about the safety of using the rungs for hand support versus the rails (Armstrong et al., 2009; Barnett and Poczynck, 2000; Hammer and Schmalz, 1992; Young et al., 2012).

It is generally agreed that three-point contact between the climber and the ladder provides more stability and is safer than two-point contact (Hammer and Schmalz, 1992; Schnorenberg et al., 2015). However, all climbers in this study utilized 2-beat movement patterns by moving their hands and feet together to the next rung in a parallel or diagonal pattern such that only two-point contact is maintained. Since the climbers were not specially instructed on their movement pattern during climbing, the 2-beat movement pattern might be the result of the way firefighters were trained.

There was a significant interaction between climbing direction and hand-hold style on peak resultant hand forces. There were substantially greater differences between ascending and descending resultant hand forces for rail-climbing than for rung-climbing (Fig. 6). During rail-climbing, the hands were pulling more in medial, posterior, and inferior directions during descending than ascending (Fig. 7). The greater hand forces during rail-climbing suggested rail-climbing may be more destabilized and fatiguing for the hands than rung-climbing. Also, the elevated forces would make descending more fatiguing for the hands than ascending. A previous study (Young et al., 2009) showed that the transmission of hand force to rails was less efficient than to rungs, and gloves can help to increase the coupling between the hands and rails as presented by several studies (Young et al., 2012; Hur et al., 2014; Beschorner et al., 2018).

Due to the specific configuration of aerial ladders on firetrucks, the handrails are at least 305 mm higher than the rungs. The higher rails caused the angle between the climber’s trunk and the ladder to increase by about 14° for rail-climbing than for rung-climbing. This difference made the climber’s posture more vertical for rail-climbing than rung-climbing, and the forces tended to shift more to the feet from the hands for rail-climbing than rung-climbing, but secondary analyses did not find foot forces to be significantly different between rail-climbing and rung-climbing. This does not affect the discussion regarding the clustered pattern of ankle-wrist distance during rung climbing versus the continuous pattern of ankle-wrist distance during rail climbing. In addition, this should not affect the identified significant interaction between climbing direction and hand-hold style on resultant hand forces.

There were several limitations to this study. The instrumented ladder was 3.4 m long, which contained only 10 rungs. The climbing speeds and movement patterns may reach steady states on a long ladder. Means of parameters of several steps were taken in this study to reduce this effect. Another limitation is that the climbers were instructed to climb with their preferred speed and pattern. This means climbers may climb with the speed and patterns they were comfortable with, but not necessarily the speed and movement pattern they would perform during intense firefighting. Also, the participants were instructed to perform rung-climbing and rail-climbing as two experimental conditions regardless of their natural method of climbing the ladder. This may add bias to their climbing mechanics. For example, participants who naturally climbed with rails may always maintain hand contact during rail-climbing, while participants who naturally climbed with rungs may maintain less hand contact during rail-climbing.

Furthermore, this study only investigated climbing on an aerial ladder at a 52.5° slope with elevated side rails, which is a very specific type of ladder used on fire trucks. Thus, the findings of this study are not transferrable to general ladder climbing scenarios.

5. Conclusions

This study shows that there were significant movement and force pattern differences between elevated rail- and rung-climbing of an aerial ladder at a 52.5° slope. Rail climbers almost continuously maintained three or more points of contact with the ladder while rung climbers only maintained three-point contact 54% of the time. Rail-climbing allows climbers to have contact of both hands with the elevated rails throughout the climbing to exert force to recover from a slip or perturbation instead of one hand during rung-climbing. Also, the ankle-wrist distances suggested that rail-climbing allows more comfortable hand placement by not restricting the location of the hands. In addition, it was shown that the average speed to ascend and descend the ladder was consistently faster (40 mm/s) for climbing with the elevated rails than with rungs. Together, these effects could be beneficial in mitigating the fall risk. On the other hand, rail-climbing associates with larger hand forces that could be more destabilizing and suggest increased hand fatigue as compared to rung-climbing.

Acknowledgments

This work was supported by a research contract from the National Institute for Occupational Safety and Health (NIOSH) [CDC Contract No. 211 −20 14–58744]. This study was initiated and conceptualized by NIOSH, and the experimental evaluation was completed at the Center for Ergonomics, University of Michigan. The methodology was jointly discussed and implemented. The experimental setup, data collection, and data reduction were completed by the University of Michigan. The authors would like to express sincere thanks to Michael Wilbur of the New York City Fire Department (retired) and Gordon Routley of the National Fallen Firefighters Foundation for their advice on aerial ladder use and special assistance on participant recruitment.

References

Armstrong TJ, Young J, Woolley C, Ashton-Miller J, Kim H, 2009. October. Biomechanical Aspects of Fixed Ladder Climbing: Style, Ladder Tilt and Carrying. Proceedings of the human factors and ergonomics society annual meeting (Vol. 53, No. 14. Sage CA, Los Angeles, CA, pp. 935–939 (SAGE Publications).

Barnett R, Poczynck P, 2000. Ladder rung vs. siderail hand grip strategies. Safety Brief (Triodyne Inc.) 16 (4), 1–15.

Barron PJ, Burgess K, Cooper K, Stewart AD, 2018. The effect of pitched and vertical ladder ergometer climbing on cardiorespiratory and psychophysical variables. Appl. Ergon 66, 172–176. [PubMed: 28958426]

Beschorner KE, Slota GP, Pliner EM, Spaho E, Seo NJ, 2018. Effects of gloves and pulling task on achievable downward pull forces on a rung. Hum. Factors 60 (2), 191–200. [PubMed: 29161154]

Bloswick DS, Chaffin DB, 1990. An ergonomic analysis of the ladder climbing activity. Int. J. Ind. Ergon 6 (1), 17–27.

Dewar ME, 1977. Body movements in climbing a ladder. Ergonomics 20 (1), 67–86. [PubMed: 837908]

Guidotti TL, 1992. Human factors in firefighting: ergonomic-, cardiopulmonary-, and psychogenic stress-related issues. Int. Arch. Occup. Environ. Health 64 (1), 1–12. [PubMed: 1399009]

Hammer W, Schmalz U, 1992. Human behaviour when climbing ladders with varying inclinations. Saf. Sci 15 (1), 21–38.

Hsiao H, 2014. Fall prevention research and practice: a total worker safety approach. Ind. Health 52 (5), 381–392. [PubMed: 25345424]

Hur P, Motawar B, Seo NJ, 2014. Muscular responses to handle perturbation with different glove condition. J. Electromyogr. Kinesiol. 24 (1), 159–164. [PubMed: 24210794]

Jensen RC, Holland CJ, 2020. Ladder safety: a taxonomy of limb-movement patterns for three points of control. Int. J. Environ. Res. Publ. Health 17 (8), 1–10. 10.3390/ijerph17082897. Article 2897.

Karger DW, Bayha FH, 1987. Engineered Work Measurement: the Principles, Techniques, and Data of Methods-Time Measurement Background and Foundations of Work Measurement and Methods-Time Measurement, Plus Other Related Material, fourth ed. Industrial Press Inc., New York, NY, pp. 91–95.

Lee YH, Cheng CK, Tsuang YH, 1994. Biomechanical analysis in ladder climbing: the effect of slant angle and climbing speed. Proc. Natl. Sci. Counc. Repub. China Part B Life Sci 18, 170.

Martin ER, Pliner EM, Beschorner KE, 2020. Characterizing the shoe-rung friction requirements during ladder climbing. J. Biomech 99, 109507. [PubMed: 31780121]

McIntyre DR, 1983. Gait patterns during free choice ladder ascents. Hum. Mov. Sci 2 (3), 187–195. Applied Ergonomics 99 (2022) 103639

National Fire Protection Association (NFPA), 2008. NFPA 1901 Standard for Automotive Fire Apparatus – 2003 Edition. NFPA Codes and Standards, National Fire Protection Association, Quincy, MA.

Oates AR, Hauck L, Moraes R, Sibley KM, 2017. The effects of haptic input on biomechanical and neurophysiological parameters of walking: a scoping review. Gait Posture 58, 232–239. [PubMed: 28822328]

Pliner E, Beschorner K, 2017. September. Effects of ladder climbing patterns on fall severity. Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 61, No. 1. Sage CA, Los Angeles, CA, pp. 940–944 (SAGE Publications).

Pliner EM, Seo NJ, Ramakrishnan V, Beschorner KE, 2019. Effects of upper body strength, hand placement and foot placement on ladder fall severity. Gait Posture 68, 23–29. [PubMed: 30439684]

Pliner EM, Novak AC, Beschorner KE, 2020. Hand-rung forces after a ladder climbing perturbation. J. Biomech. 106, 109790. [PubMed: 32517996]

Schnorenberg AJ, Campbell-Kyureghyan NH, Beschorner KE, 2015. Biomechanical response to ladder slipping events: effects of hand placement. J. Biomech. 48 (14), 3810–3815. [PubMed: 26431752]

Sienko KH, Balkwill MD, Oddsson LI, Wall C, 2013. The effect of vibrotactile feedback on postural sway during locomotor activities. J. NeuroEng. Rehabil. 10 (1), 93. [PubMed: 23938136]

Simeonov P, Hsiao H, Armstrong T, Fu Q, Woolley C, Kau TY, 2020. Effects of aerial ladder rung spacing on firefighter climbing biomechanics. Appl. Ergon. 82, 102911. [PubMed: 31422289]

Socias CM, Menéndez CKC, Collins JW, Simeonov P, 2014. Occupational ladder fall injuries—United States, 2011. MMWR. Morbidity and mortality weekly report 63 (16), 341.

Song S, Choi H, Collins SH, 2020. Using force data to self-pace an instrumented treadmill and measure self-selected walking speed. J. NeuroEng. Rehabil. 17, 1–14. [PubMed: 31900169]

Szychlinska MA, Dullaert K, Beumer A, Nsir H, Guglielmino C, Mazzone V, Giunta S, 2017. Ergonomics of prehensility in pushing and pulling motions: an anatomical and biomechanical overview. Journal of Functional Morphology and Kinesiology 2 (1), 6.

Vi P, 2008. October. Effects of ladder types on energy expenditure and forearm force exertion during ladder climbing. In: 2008 National Occupational Injury Research Symposium (NOIRS). Pittsburgh, Pennsylvania.

Young JG, Woolley C, Armstrong TJ, Ashton-Miller JA, 2009. Hand-handhold coupling: effect of handle shape, orientation, and friction on breakaway strength. Hum. Factors 51 (5), 705–717. [PubMed: 20196295]

Young JG, Woolley CB, Ashton-Miller JA, Armstrong TJ, 2012. The effect of handhold orientation, size, and wearing gloves on hand-handhold breakaway strength. Hum. Factors 54 (3), 316–333. [PubMed: 22768636]

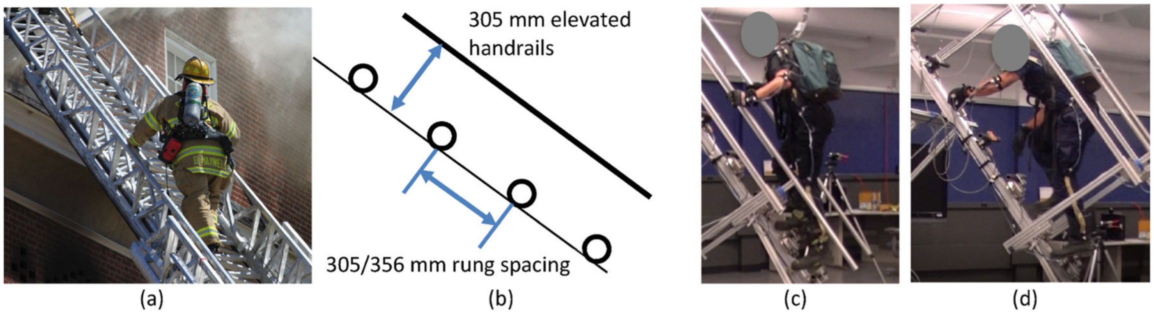


Fig. 1.

(a) Firefighter rail-climbing ladder[1]; (b) Diagram shows that the definition of rung spacing and elevated handrails; (c) Participant performs rail-climbing on the ladder at 52.5○; and (d) Participant performs rung-climbing on the ladder at 52.5○. [1] Image adapted from globalfirefighters.blogspot.com on Feb 20th, 2020

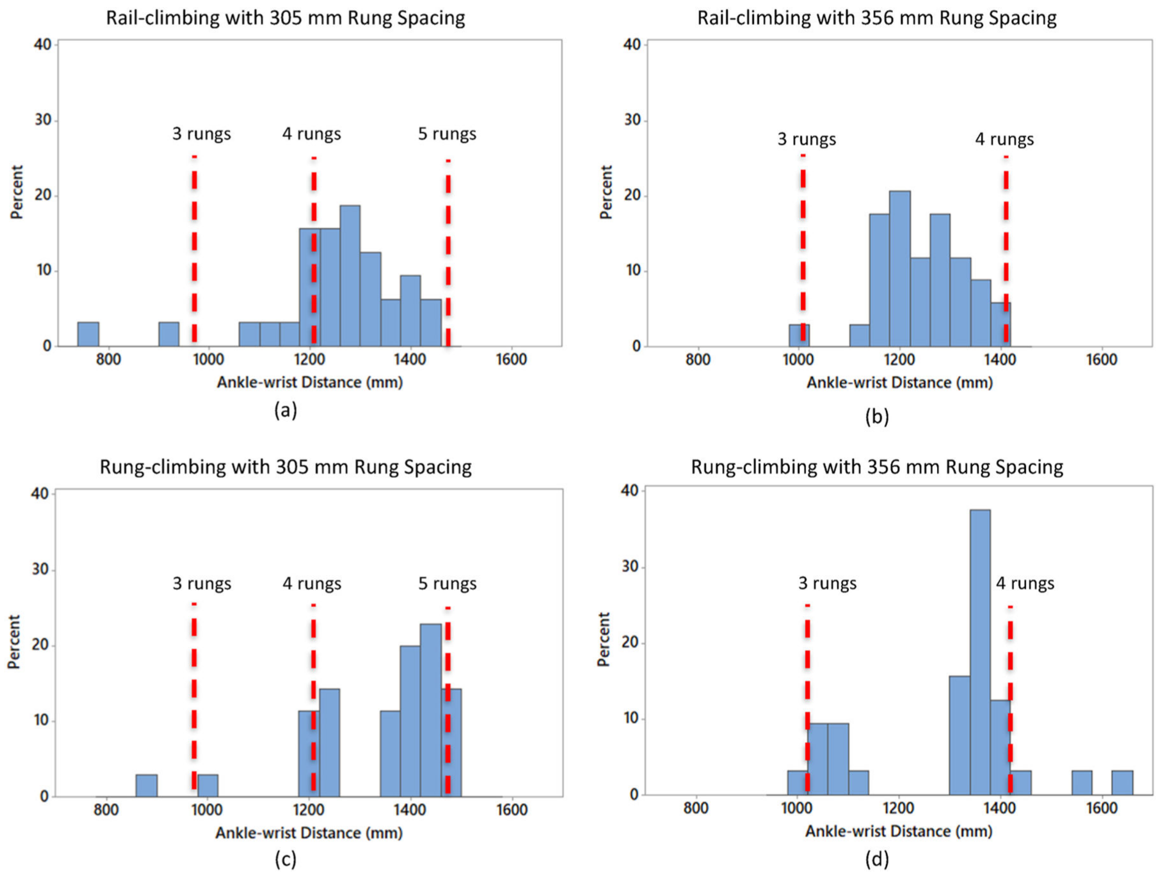


Fig. 2.

Distribution of ankle-wrist distance during each climb cycle for rail-climbing (a and b) and rung-climbing (c and d) for 305 mm rung spacing (a and c) and 356 mm rung spacing (b and d) from 19 participants with 8 climb cycles for all participants with both climbing directions pooled. Ankle-wrist distances were clustered around the distances of three, four, and five multiples of rung spacing for rung-climbing with 305 mm rung spacing and around the distances of three and four multiples of rung spacing for rung-climbing with 356 mm rung spacing. Ankle-wrist distances for rail-climbing were continuously distributed. The distances of 3, 4, and 5 rungs are shown in dashed lines.

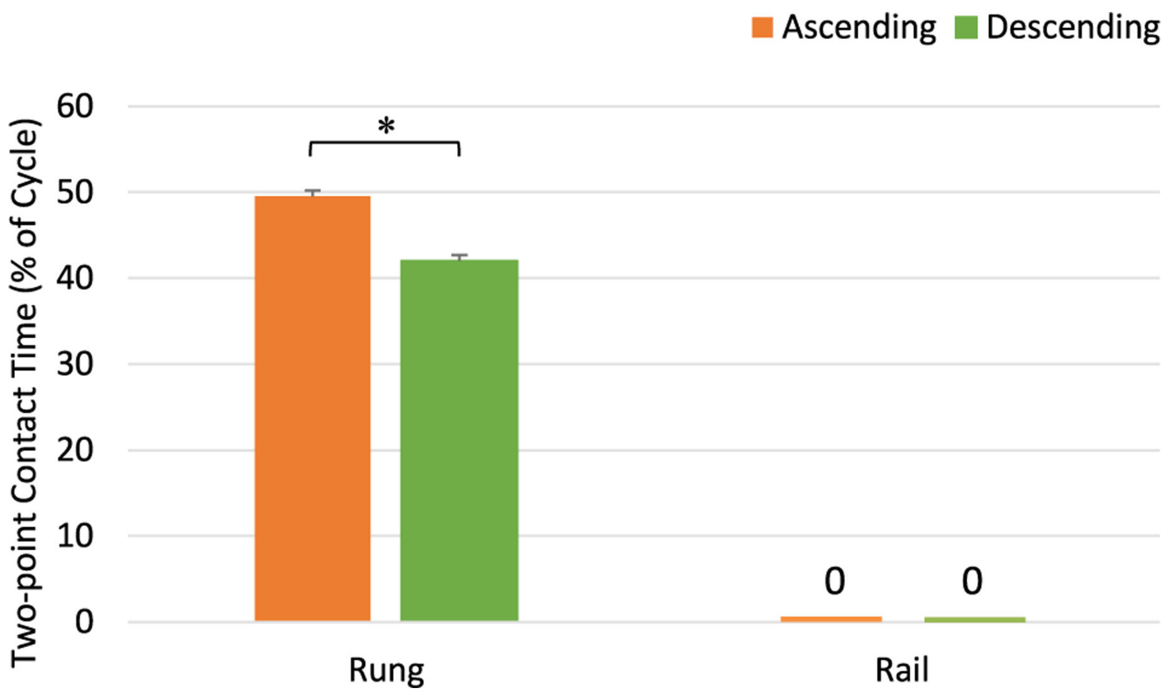


Fig. 3.

Climbing direction and hand-hold style interaction on two-point contact time pooled for 19 participants. The plot is made based on mean and standard error. The rail-climbing condition had no two-point contact observed.

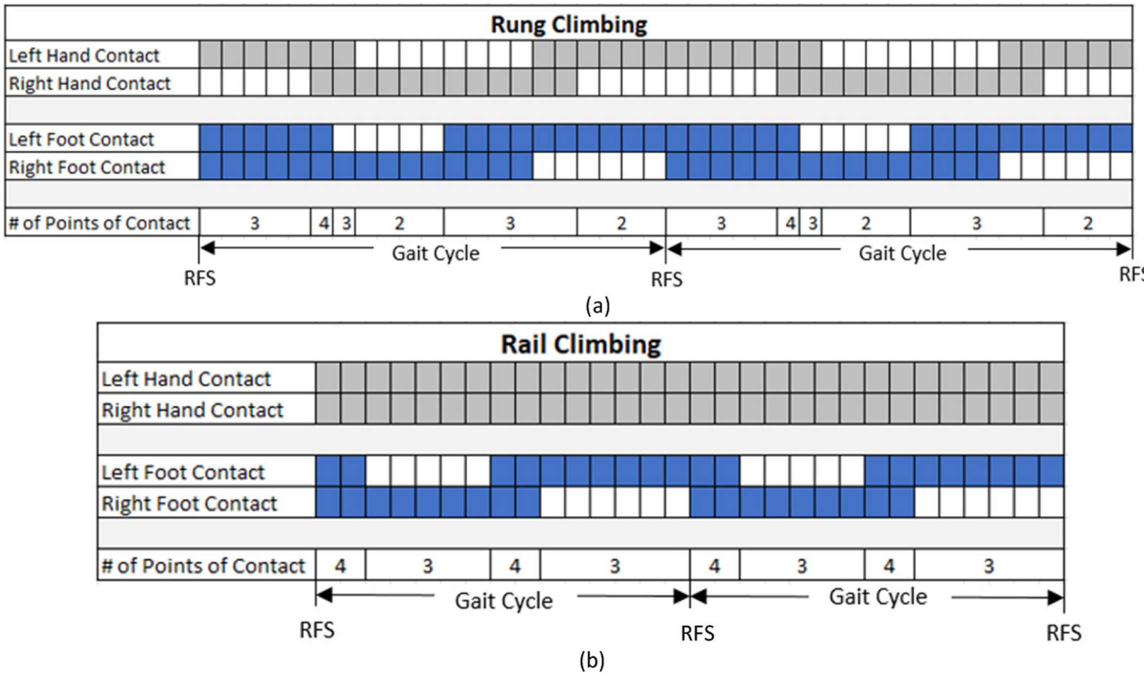


Fig. 4.

Sample diagram of hand and foot contact during two complete climb cycles for (a) rung-climbing and (b) rail-climbing for participant #14 ascending a ladder with 305 mm rung spacing. Grey blocks represent hand contact, and blue blocks represent foot contact (with force exceeding the threshold of 1 N). The climb cycle was defined as from right foot strike (RFS) to right foot strike. Each cell in the diagram represents 100 ms. There were regular two-point contact periods for rung-climbing and no two-point contact periods for rail-climbing. The duration of the two-point contact is shown in the last row of each figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

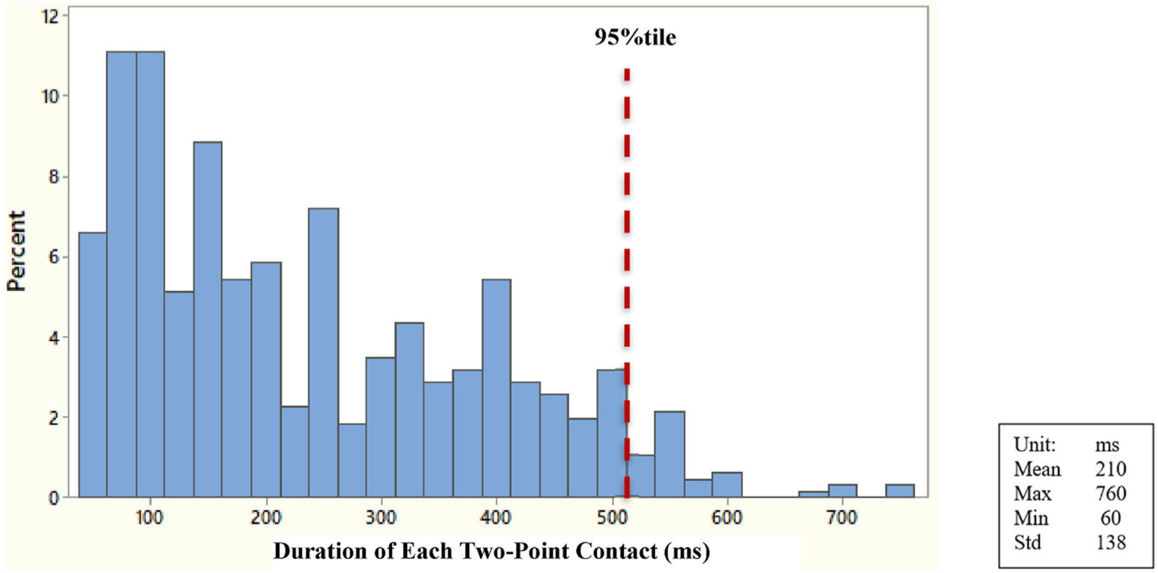


Fig. 5.

Percent of two-point contact periods (as shown in Fig. 4(a)) with all climb cycles pooled for all participants during the rung-climbing (up & down pooled, 305 & 356 mm rung spacing pooled).

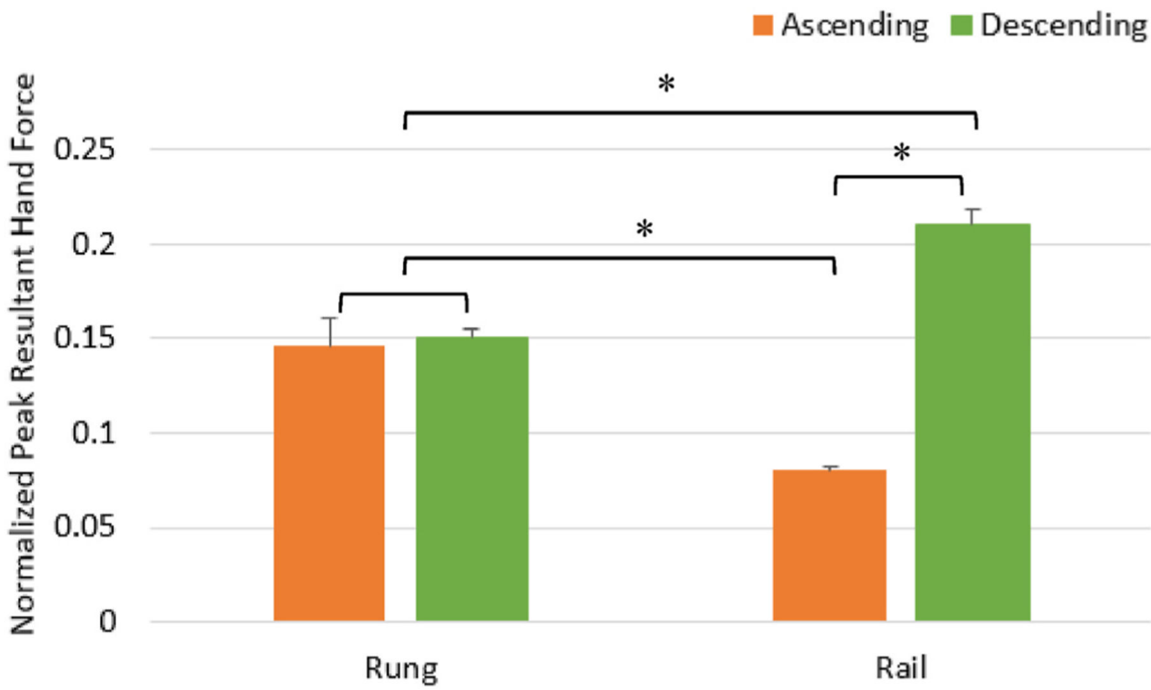
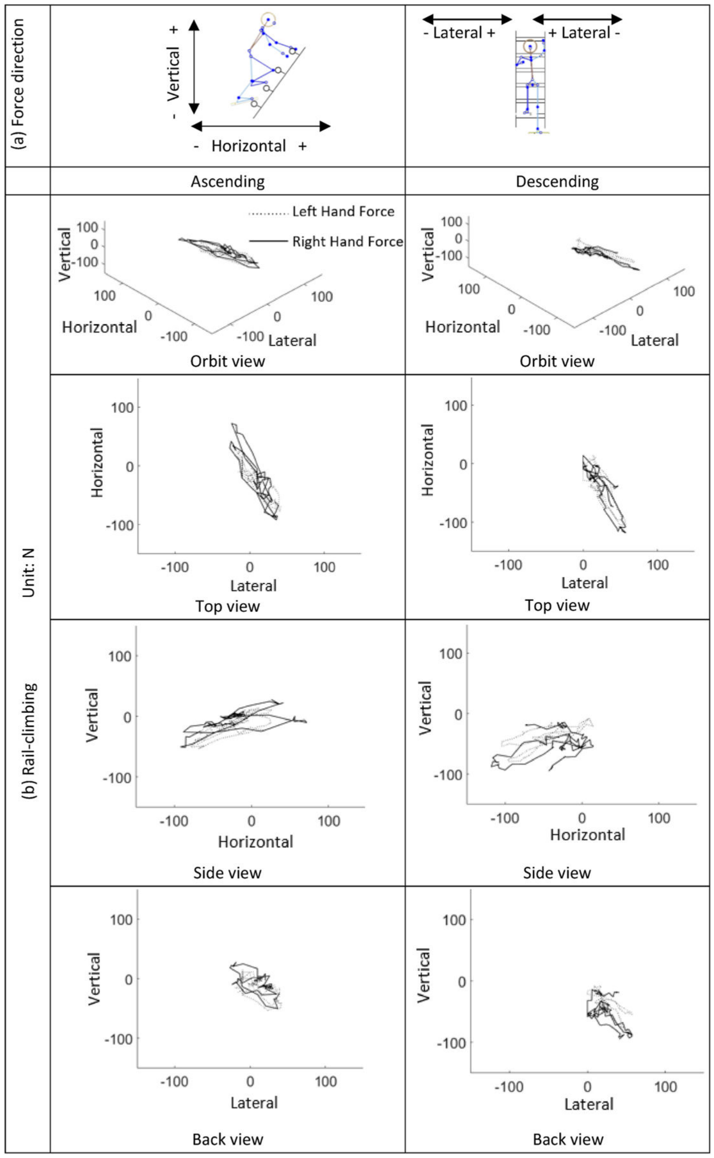


Fig. 6.

Climbing direction and hand-hold style interaction on normalized peak resultant hand force pooled for 19 participants (0.08 ± 0.03 for ascending with rail-climbing, 0.21 ± 0.07 for descending with rail-climbing, 0.15 ± 0.03 for ascending with rung-climbing, 0.15 ± 0.05 for descending with rung-climbing). The plot is made based on the mean and standard error of the force measurement.


(a) Force direction
- Vertical +
- Horizontal +
- Lateral +
+ Lateral -
Ascending
Descending
Left Hand Force
Right Hand Force
(b) Rail-climbing
Unit: N
Orbit view
Top view
Side view
Back view
Vertical
Horizontal
Lateral

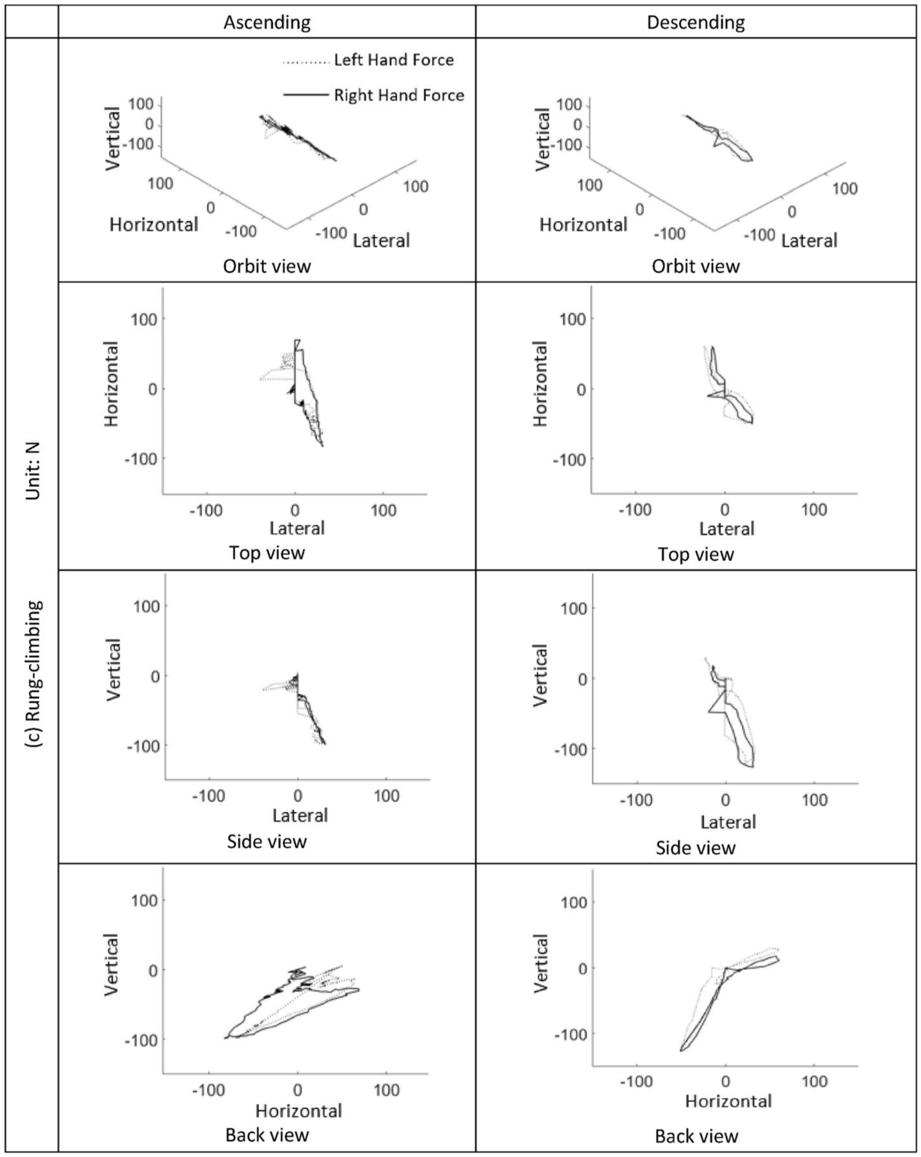


Fig. 7.

(a) The definition of hand-force directions (lateral force direction: lateral/medial −/+; horizontal force direction: posterior/anterior −/+; vertical force direction: inferior/superior −/+), and sample 3D plots of hand forces for ascending and descending during (b) rail-climbing and (c) rung-climbing for participant #18 with 305 mm ladder rung spacing.

Table 1

ANOVA table for all main effects with mean ± std, F-value, and p-value.

Variables	Climbing Speed (m/s)	Ankle-wrist Distance (mm)	Two-point Contact (% of Gait)	Normalized Peak Hand Force (%)
Gender(F vs. M)	0.38 ± 0.05 vs. 0.43 ± 0.06($F = 1.02$, $p < 0.022$)	1275 ± 120 vs. 1316 ± 130($F = 1.93$, $p = 0.056$)	0.18 ± 0.22 vs. 0.22 ± 0.30($F = 1.26$, $p = 0.210$)	0.14 ± 0.06 vs. 0.15 ± 0.08($F = 0.00$, $p = 0.963$)
Hand-hold(Rung vs. Rail)	0.39 ± 0.05 vs. 0.43 ± 0.06($F = 41.16$, $p < 0.001$)	1329 ± 140 vs. 1254 ± 96($F = 13.49$, $p < 0.001$)	0.46 ± 0.17 vs. 0 ± 0($F = 13.18$, $p < 0.001$)	0.15 ± 0.04 vs. 0.14 ± 0.08($F = 1.09$, $p = 0.071$)
Direction(Up vs. Down)	0.42 ± 0.07 vs. 0.39 ± 0.04($F = 31.47$, $p < 0.001$)	1297 ± 132 vs. 1287 ± 119($F = -0.34$, $p = 0.732$)	0.29 ± 0.35 vs. 0.11 ± 0.16($F = -5.98$, $p = 0.067$)	0.13 ± 0.05 vs. 0.19 ± 0.07($F = 136.89$, $p < 0.001$)
Rung Spacing(305 vs. 356)	0.42 ± 0.06 vs. 0.4 ± 0.05($F = 14.22$, $p < 0.001$)	1314 ± 121 vs. 1271 ± 127($F = 4.12$, $p = 0.045$)	0.21 ± 0.29 vs. 0.20 ± 0.29($F = -0.38$, $p = 0.706$)	0.14 ± 0.06 vs. 0.15 ± 0.07($F = 0.96$, $p = 0.329$)

* The significant ($p < 0.05$) interaction terms are shown in detail in Figs. 3 and 6.