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Effects of aerial ladder rung spacing on firefighter climbing biomechanics

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ABSTRACT

This study investigated the effects of aerial ladder rung spacing on firefighter climbing biomechanics. Ten female and 9 male firefighters ascended and descended instrumented ladders with rungs spaced at 356 mm (current design) and 305 mm in a laboratory setup. The climbing tests were performed at five ladder slope and handrail conditions: 30° with low (305 mm) and high (914 mm) handrails, 52.5° with and without a low handrail, and 75° without a handrail. Foot and hand forces and body movements were recorded and used to calculate joint moments of the upper and lower body. Reduced rung spacing resulted in reduced foot forces, reduced hand forces, and reduced ankle transverse moment. It was also associated with increased climbing speed for female climbers, and increased ankle vertical overshoot. The results indicate that reduced rung spacing on aerial ladders may lead to lower biomechanical stress; better climbing efficiency and safety; and reduced climbing speed disparity across sexes.

1. Introduction

1.1. Background

The National Fire Protection Association (NFPA) estimates that there were approximately 1,160,450 firefighters in the U.S. in 2015, including 345,600 (30%) career firefighters and 814,850 (70%) volunteer firefighters (NFPA, 2017). Of the estimated 62,085 firefighter injuries in year 2016 in the line of duty, 24,213 (39%) occurred during fire-ground operations. Overexertion and strain (27%) and fall, slip, or jump (21%) were the two leading causes of fire-ground injuries (NFPA, 2017). Accessing and using the aerial apparatus has been identified by the firefighter community as a significant source of risk of falls and overexertion injuries.

Firefighters often climb aerial ladders up to 30 m long, positioned at various angles. They usually wear heavy protective equipment and may be carrying additional equipment related to fighting fires or rescuing occupants from burning buildings. They may work in extremely cold or hot environments. Climbing is regarded as a physically demanding and fatiguing task. High physical demands and fatigue can reduce work performance and increase risk of fall incidents and musculoskeletal injuries (Hsiao and Simeonov 2001).

This study is motivated by the concern that the 356 mm rung spacing found on most aerial ladders may not be optimal – especially for firefighters with small body sizes, including female firefighters. Body size affects the ability to reach from one rung to the next and can be a barrier for persons with small body sizes (male or female). In 2015 there were 85,100 female firefighters in the US fire service, accounting for 7% of all firefighters (NFPA, 2017). A national survey shows that average female firefighters are 102 mm shorter in stature than average male firefighters (Hsiao et al., 2014).

The Standard for Automotive Fire Apparatus (NFPA 1901: Chapter 19, 2003 Edition), specifies that aerial ladder rungs shall be uniformly spaced between 298 and 356 mm, and 356 mm rung spacing is found on most existing aerial ladders (NFPA, 2008). The reason for 356 mm versus 298 mm rung spacing is open to speculation. Most likely the 356 mm spacing has been considered best for "locking in" – a practice in which firefighters inserted one leg above a rung and then hooked the foot of that leg under a lower rung to stabilize their body while they worked from the ladder. While historically this practice has been routinely used with fire service portable straight and extension ladders, it is not currently used with the contemporary aerial ladders. Another possible design consideration is that 356 mm spacing required fewer rungs and ladders may be lighter and less costly than 305 mm spacing. In contrast to the NFPA standard, the American National Standard for Ladders (ANSI A14 2017) recommends 305 mm rung spacing for

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portable ladders.

1.2. Ladder climbing

Ladder climbing has been related to walking (Dewar, 1977) in that the body weight is alternately transferred between the feet during each gait cycle. In the ladder climbing cycle, the body weight has to be transferred both forward and up which resembles more closely the process of climbing stairs, described to include the stages of weight acceptance, pull-up, forward continuance, foot clearance, and foot placement (McFadyen and Winter, 1988). In ladder climbing, the support surface provided by the rungs is restricted (narrow), which challenges stability of the foot and the body especially in the sagittal plane. Furthermore, the support provided by the rungs is often unstable since the ladder structure may move, bend, and sway when climbed. Therefore, in ladder climbing the hands are used both to support and stabilize the body (Dewar, 1977; McIntyre, 1983; Armstrong et al., 2009).

In walking, the weight shifts between the heel and the toe and develops gradually on the toe as the weight is shifted to the opposite foot. In ladder climbing, the body weight plus inertia forces are transferred on the forward part of the foot as the subject steps up or down to the next rung. Some of the force on the feet may be reduced by vertical forces on the hand, but previous studies show that most of the force to lift the body from one rung to the next is from the feet (Bloswick and Chaffin, 1990; Armstrong et al., 2009). In walking on a level surface the stride length is freely selected based on the personal characteristics, physiological state, and preference, and is also varied to accommodate balance control. In ladder climbing the stride has a fixed length determined by the rung position in space which is defined by the ladder angle and ladder rung spacing.

1.3. Rung spacing

Change in ladder rung spacing may affect human biomechanics in a climbing stride in three ways, by: (1) modifying the whole body spatial configuration and the associated joint angles, (2) changing the horizontal and vertical transfer paths of the body center of mass (COM), and (3) altering the hand and foot placement target positions in space. General physics considerations dictate that, for a constant climbing speed, larger rung spacing will lead to less frequent but longer climbing strides involving higher physical efforts while smaller rung spacing will result in a more frequent but shorter climbing strides requiring lower physical efforts.

The changes in the body spatial configuration and angles of joint motion associated with ladder climbing at different rung spacing may alter the magnitude of hand and foot forces and joint moments. Previous studies with all male participants reported small but significant effects of rung spacing (305 mm vs 381 mm) on hand and foot forces at 70°–90° ladder angles (Bloswick and Chaffin, 1990) as well as significant increases in hip, knee, and ankle joint moments with increased (300 mm–350 mm) rung spacing at a 77° ladder angle (Hoozemans et al., 2005). Using both male and female participants, Kamarajugadda (2014) also found that changes in rung spacing had a significant effect on knee and hip joint moments for vertical ladder climbing and that the existing rung separation (305 mm) used in wind towers was better than larger (381 mm) or shorter (254 mm) rung separations.

A specific rung spacing may not be optimal for all climbers due to their anthropometry, physical and physiological state, and preference. For example, a large rung spacing can be a challenge to shorter users. Dewar (1977) found that shorter subjects had to flex hips and knees more to lift their feet onto a rung. McIntyre (1983) noted that the hand forces exerted by short subjects were higher than those of tall subjects and that the hand forces of short subjects increased more rapidly as rung separation increased.

An increase in rung spacing can also lead to an increase in the work to lift and transfer the body center of mass (COM) in both vertical and lateral directions. Correspondingly, it will increase the required muscle power and energy expenditure, which may cause muscle fatigue. A rung separation greater than 356 mm was found to require a ‘‘fatiguing’’ exertion (Chaffin et al., 1978) and continuous climbing with increased rung spacing (356 mm) was more fatiguing than with the 305-mm spacing (Bloswick, 1999).

Furthermore, in ladder climbing, the hand and foot transition movements can be regarded as target-directed movements, which are in line with the Fitts' law (Fitts, 1954). Foot motions require nearly twice as much transition time as hand motions (Hoffmann, 1991), and increases in rung spacing can increase both hand and foot transition times and movement errors, which may result in slipping or tripping on the rungs.

The risk of slipping on the rung may also be related to optimal foot placement on the rung (the ankle-rung distance) in the anterior-posterior direction. In climbing, forces may be concentrated in one location on the sole between the ankle and the toe and may produce high moments that tend to dorsiflex the foot. The ankle may not be able to resist the resulting moments if the point of contact is too close to the toe, which can force the foot into an extreme rotation and cause the foot to slide off the rung (Pliner et al., 2014). Even if the climber has sufficient ankle strength, he or she may not be able to respond fast enough to prevent a slip (Schnorenberg et al., 2015). This is especially a concern for firefighters when they are in a hurry to put out a fire or rescue occupants while using a ladder.

The moment at the ankle is related to the vector product of the ankle-rung moment arm and the resultant force on the foot. The foot force is mostly due to climber's weight and inertia and is acting downward parallel to gravity. The ankle moment arm is the ankle-rung distance in the anterior-posterior direction. Bloswick and Chaffin (1990) reported moments from 30% to 48% of maximum ankle strength versus 15%–25% for the hip and 8%–10% for the knee. Ankle-rung distance variations in the anterior-posterior direction due to ladder or behavioral factors can have a profound effect on the ankle moment and the climber's ability to maintain foot placement.

The risk of tripping or stumbling on a ladder rung may be associated with suboptimal vertical overshoot (vertical landing clearance) – the distance that the foot is lifted above a rung as a person steps up or down to the next rung. Trips can occur in both walking and climbing if the foot is not lifted high enough to clear obstructions between the start and the end of the step (Kesler et al., 2016). Trips and falls have been studied extensively for walking, but not for climbing. The vertical overshoot provides an indication of how close the climber comes to tripping (Kesler et al., 2016). Movement errors increasing the overshoot will reduce the risk of tripping. This is analogous to exerting excess force to prevent an object from slipping out of one's hand (Frederick and Armstrong, 1995). Johansson and Westling (1984) refer to this as a “safety margin.” This term could be used to refer to toe clearance as well.

The existing studies investigating the effects of rung spacing on ladder climbing biomechanics have been limited to ladder slopes in the range of 65°–90°, slopes commonly seen in general industry. The effects of rung spacing at various slope conditions of aerial ladders used in firefighting have not been adequately investigated. Moreover, the effects of rung spacing on ladder climbing biomechanics remain inconclusive in the literature. Bloswick and Chaffin (1990) reported that at 70°–90° ladder angles, the effects of rung spacing were small. Hoozemans et al. (2005), however, found that at the steep ladder angle of 77°, window washers preferred the larger rung spacing (350 mm vs 300 mm) in spite of the associated increased biomechanical load.

1.4. Study objective

The objective of this study was to explore the effects of aerial ladder rung spacing on climbing behavior and biomechanics of firefighters under various firefighting or rescue scenarios (i.e., 30°–75° aerial ladder settings that reflect far-reaching and height-reaching environmental conditions). Comparative evaluation of the effects of 356 mm vs 305 mm rung spacing over a range of typical aerial ladder angles is needed to generate a scientific knowledge base for improving the design of fire-truck aerial ladders for more efficient and safer use by the diverse firefighter community.

2. Method

2.1. Participants

Ten male and ten female firefighters were recruited from the local fire departments in southern Michigan. The participants were all trained firefighters and had professional ladder climbing training and experience. All participants were screened to identify any conditions that might make them unfit to participate in the study. The goals of the study, experimental procedures, and possible risks were explained to the participants and they signed an informed consent form approved by the Institutional Review Boards of the University of Michigan and NIOSH. The motion tracking and force data of one male participant were missing for some reason; so data are reported for nineteen out of the twenty participants. Participant age, height, weight, and correlations are shown in Tables 1a–1b.

2.2. Experimental design

The experiment was designed to evaluate the effect of ladder rung spacing and its interactions with other ladder geometry characteristics, climbing tasks, climbing styles, and participant sex on climbing biomechanics and climbing performance variables.

Independent variables: The ladder geometry factors included rung spacing, 305 mm and 356 mm; ladder slope relative to horizontal, 30°, 52.5° and 75°; and handrail height, 305 mm ("low") and 914 mm ("high") for the 30° slope as well as 305 mm ("low") handrail height for the 52.5° slope. The climbing task variable was climbing direction, up (ascending) and down (descending). The two climbing styles were "rails holding" applicable for ladder slopes 30° and 52.5° and "rungs holding" applicable for ladder slopes 52.5° and 75°. There were nine male and ten female participants for studying the sex factor. In data analyses, the ladder slope and the associated hand holding conditions were treated as one compound variable (slope-rail) with the following 5 levels: 30°-high-rail, 30°-low-rail, 52.5°-low-rail, 52.5°-no rail (rungs), and 75°-no rail (rungs). Comparing the corresponding levels of this compound variable allows evaluation of the effects of ladder angle (30° vs 52.5° with low-rail, and 52.5° vs 75° with rungs), handrail height (high-rail vs low-rail at 30° slope), and climbing style (low-rail vs rung at 52.5°).

Dependent variables include kinetic, kinematic, and performance measures. The kinetic variables included the horizontal (anterior-posterior), lateral (along the rung axis), and vertical (along gravity) peak hand and foot forces which were measured using the instrumented ladder setup; the measured peak forces were then used to calculate the resultant peak hand and foot forces which were then normalized to participants' weight. Other kinetic-related measures included the frontal, sagittal, and transverse joint moments at the ankle, hip, and shoulder, which were estimated from force data with MatLab (MathWorks, Natick, MA, USA) along with the algorithm of the University of Michigan 3D Static Strength Prediction Program™ (3DSSPP) (Chaffin et al., 1999), and then normalized to participants' weight. Frontal moments are defined as torques about the horizontal joint axis; sagittal moments as torques about the lateral joint axis; and transverse moments as torques about the vertical joint axis. The kinematic measures included anterior-posterior ankle-rung distance, ankle vertical overshoot, and relative hand and foot contact times describing the temporal characteristics of the climbing stride (Dewar, 1977). The performance measure was climbing speed calculated from the kinematic data.

Table 1b
Correlations between participant sex, height, and weight.

	Sex	Ht1 (cm)	Ht2 (cm)	Wt1 (Kg)	Wt2 (Kg)
Sex	**1**				
Ht1 (cm)	**.53**	**1**			
Ht2 (cm)	**.53**	**.99**	**1**		
Wt1 (Kg)	.31	**.62**	**.62**	**1**	
Wt2 (Kg)	.28	**.61**	**.61**	**.99**	**1**

*All correlations in bold are significant $p \leqslant 0.05$.
Ht1: height without shoes.
Ht2: height as tested.
Wt1: weight without equipment.
Wt2: weight as tested.

2.3. Equipment

A ladder was constructed using a single 3.4 m aluminum extrusion profile to support the rungs. The 31.8 mm diameter steel rungs were covered with rubberized stair tread material with traction ridges parallel to the long axis of the rung (see Fig. 1).

Two diagonal links that support the ladder were attached to a horizontal motorized lead screw to adjust ladder slope between 30° and 75°. Spacers were inserted between the rungs so that the ladder could be quickly configured for 305 or 356 mm rung spacing. Rung spacing required 10–15 min of changeover time. A fall arrest system (Miller Fall Protection - Honeywell Safety, Franklin, PA, USA) was attached to the lab ceiling structure and connected to the harness worn by the participants (Fig. 2).

An NDI Optotrak Certus (NDI Waterloo, Ontario, Canada) with two sensor units (three cameras each) was used to record locations and movements of wrists, elbows, shoulders, hips, knees, and ankles at 100 Hz. Markers were also placed on ladder rungs 3 and 7 for converting global to local ladder coordinates. Samples of ankle and wrist marker recordings are provided in the Appendix (Figure A1).

Horizontal ankle-rung distances were computed as the anterior-posterior distance (y_{ankle} - y_{rung}) after the ankle achieved a stable position on the rung and the opposite foot was moving up or down to the next rung. Vertical overshoot was computed as the distance between the ankle height local maximum and ankle height at step end (z_{max} – z_{end}). Typical ankle trajectories for ascending and descending for one complete trial by one participant on a ladder with 305 mm rung spacing

Table 1a
Participant data.

	Female (n = 10)					Male (n = 9)				
	Age	Ht1 (cm)	Ht2 (cm)	Wt1 (Kg)	Wt2 (Kg)	Age	Ht1 (cm)	Ht2 (cm)	Wt1 (Kg)	Wt2 (Kg)
Min	23	161	163	62	66	20	162	166	54	57
Max	53	175	180	108	110	53	185	188	109	112
Avg	32.8	167.7	171.3	74.2	77.4	35.6	175	178.7	82.8	85.1
Stdev	10.4	5.1	5.5	13.7	13.6	12	7.3	7	14.4	14.4

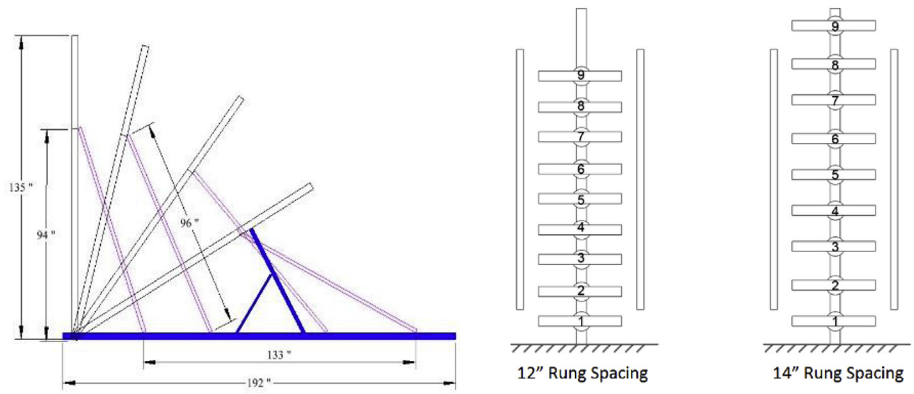


Fig. 1. Adjustable ladder with instrumented rungs and rails.

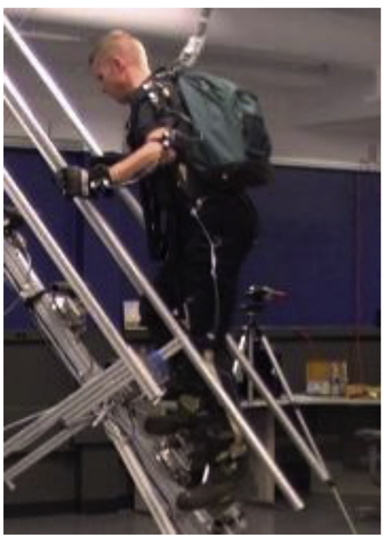


Fig. 2. Participant #3 (male, 184.5 cm, 83.9 Kg) climbing a ladder with 356 mm rung spacing at 52.5° angle using "low" 305 mm rails.

at 52.5° slope are shown in the Appendix (Figure A2).

The climbing speed along the ladder was computed based on the average of right and left foot time to move from rung 2 to 4 and rung 3 to 5 and the distance between the rungs.

Rungs 2–5 were mounted on 6-axis force gauges (Theta US-600-3600, ATI, Apex, NC, USA) to record foot forces and rungs 6–9 were mounted on 6-axis force gauges (MC3A-6–1000, AMTI, Watertown, MA, USA) to record hand forces. Rails (38 mm diameter) were attached to the sides of the ladder 838 mm apart using 3-axis force gauges (3A120-2 KN–C11, Interface, Scottsdale, AZ, USA) at each end such that they could be quickly configured for 305 mm or 914 mm height with respect to the plane of the rungs and the long axis of the ladder. The axes of the force gauges were oriented with respect to the major axes of the ladder; vertical and horizontal force components parallel and perpendicular to gravity were computed based on the known ladder angle relative to horizontal. Analogue force data were sampled at 100 Hz using the NDI data acquisition system to ensure synchronization with the motion capture data.

Hand forces from the rail and rung force transducers, aligned with the long (z) and lateral (x) axis of the ladder, were imported into MatLab (MathWorks, Natick, MA, USA) so that they could be rotated to global coordinates. Vertical, horizontal, and lateral foot force recordings for rungs 2 and 3 or rungs 3 and 4 were used to capture a complete cycle of the right and left feet climbing rung over rung. Resultant forces were computed from lateral (x), horizontal (y), and vertical (z) forces.

Sample recordings of hand and foot forces for 356 mm rung spacing are shown in the Appendix (Figure A3). The time from the onset to the end of force on a given rung and the time from the beginning of force on one rung and the next rung were computed for 8 replications of each hand and foot for each condition. Hand forces for handrail climbing did not follow a discrete pattern as in climbing with hands on rungs. Hand movement cycles were arbitrarily defined as starting when the corresponding foot-rung force exceeded zero and ended when it returned to zero. An example of the temporal relationship between hand and foot forces for rung and rail climbing at ladder slope 52.5° are provided in the Appendix (Figure A4).

Peak forces during the contact phase were computed based on one complete cycle for eight replications of the right and the left hand and foot. An example of horizontal and vertical hand and foot forces at slope 52.5°, using "low" 305 mm rails and pooled for rung spacing and climbing direction, is shown in the Appendix (Figure A5).

2.4. Procedure

The participants brought their own work boots and gloves and climbed at a self-selected normal pace. 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 et al., 2014). For each ladder configuration, participants practiced climbing until they were comfortable with the procedure and then were asked to climb with their comfort speed for data collection. Each participant completed 8 trials in which they climbed to the top ladder rung where they waited 5 s before descending. Following a 5-s pause at the bottom of the ladder, they repeated the process for a total of 8 replications. Participants rested a minimum of 3 min while the ladder was reconfigured for the next condition. To control for and average out any fatigue and learning effects, half of the participants were first tested on a ladder with 305 mm rung spacing and then were tested on a ladder with 356 mm rung spacing; the sequence was reversed for the other half of the participants. The ladder slope-rail conditions were randomized within each rung-spacing test condition.

2.5. Statistical analysis

For all dependent variables, repeated measures analyses of variance (ANOVAs) were performed using the SAS MIXED procedure to evaluate the effect of different experimental conditions. In this mixed model approach, the fixed effects included three independent variables: rung spacing, climbing direction, and slope-rail; one covariate variable of sex; and participant was used as random effect. The analysis included two-way interaction terms in the final model. Various models were used to find the appropriate covariance structure of observations within each participant. A model that provided the best fit was selected for final analysis. For post-hoc multiple comparisons, the Bonferroni-adjustment was used to determine significant differences among the experimental

Table 2
ANOVA table for performance and motion data.

	Climbing Speed	Foot Contact Time, %	Hand Contact Time, %	Ankle Horizontal Moment Arm	Ankle Vertical Overshoot
Sex	*				
Direction	**	*		**	**
Slope-Rail	**	**	**	**	**
Rung Spacing	*				**
Sex x Direction					
Sex x Slope-Rail				*	
Sex x Rung S	*				
Direction x Slope-Rail		**			**
Direction x Rung S		*			
Slope-Rail x Rung S					*

**p < 0.001; * 0.001 ≤ p ≤ 0.05.

conditions. All significance level (α) used for this study was set at 0.05.

Point biserial correlation coefficients were used to examine the association between sex and height, and sex and weight. Pearson correlation coefficients were used to examine the correlation between height and weight. Statistically significant correlation coefficients were used to classify the strength of the association between comparison groups as: r = 0–0.19 (very weak), r = 0.20–0.39 (weak), r = 0.40–0.59 (moderate), r = 0.60–0.79 (strong) and r = 0.80–1.0 (very strong) (Campbell and Swinscow, 2009).

Statistical Analysis System (SAS) software (SAS Institute Inc., Cary, NC, USA) was used to perform all data analyses. Prior to any statistical testing, the normality assumption was examined using a probability plot.

3. Results

A 2 x 2 x 5 x 2 (sex, climbing direction, slope-rail, and rung spacing) repeated measures ANOVA was performed for all dependent variables. The significant effects on performance and motion variables, including climbing speed, foot and hand contact time, ankle horizontal moment arm, and ankle vertical overshoot, are included in Table 2, on the normalized foot and hand force data – in Table 3, and on the normalized hip, knee, and ankle joints moments – in Table 4. The results gave priority to the dependent variables which revealed significant effects and interactions for the rung spacing factor since rung spacing was the main focus of the study. The multiple significant main effects and interactions of the complex slope-rail variable were intentionally left out (due to space limitations) and will be addressed in a separate publication.

3.1. Climbing speed

Rung spacing: A significant effect of rung spacing demonstrated that reducing the rung spacing from 356 mm to 305 mm resulted in a 4.6% increase (p = 0.0017) in climbing speed. The significant interaction of rung spacing and sex (p = 0.0129) further indicated that this effect was significant for the female climbers (0.38 m/s vs 0.41 m/s or 7.6%, p = 0.0013) but not the male climbers (0.43 m/s vs 0.44 m/s or 1.6%, p = 1.0000) (Fig. 3).

Climbing direction: There was a significant effect of climbing direction; climbing down (descending) resulted in a decrease (8.8%, p = 0.0003) in climbing speed, as compared to climbing up (ascending).

Sex: A significant effect of sex revealed that overall, female climbers were 10.0% slower (p = 0.0022) than male climbers (0.39 m/s vs 0.44 m/s). The significant interaction between sex and rung spacing (p = 0.0129) further disclosed that female climbers were significantly slower than the male climbers only at 356 mm rung spacing (0.38 m/s vs 0.43 m/s or decrease of 12.5%, p = 0.0028) but not at 305 mm rung spacing (0.41 m/s vs 0.44 m/s decrease of 7.4%, p = 0.1430) (Fig. 3).

3.2. Normalized hand and foot forces

Rung spacing: A significant effect of rung spacing demonstrated that reducing the rung spacing from 356 mm to 305 mm resulted in a 8.6% decrease (p = 0.0003) in the horizontal normalized peak foot force. The significant interactions of rung spacing and climbing direction for vertical (p = 0.0010) and resultant (p = 0.0015) normalized peak foot forces further disclosed that the reduced rung spacing resulted in significant decreases of vertical (3.7%, p = 0.0228) and resultant (3.7%, p = 0.0153) normalized peak foot forces only in ascending and not in a descending climbing direction (Fig. 4). Significant effects of rung spacing for hand forces showed that the reduced rung spacing was also associated with decreases in vertical (9.7%, p = 0.0018) and resultant (5.1%, p = 0.0458) normalized peak hand forces.

Climbing direction: Significant effects of climbing direction on foot forces indicated that climbing down (descending) as compared to climbing up (ascending) was associated with an increase in normalized horizontal peak foot force (12.0%, p = 0.0199), and decreases in lateral (9.2%, p < 0.0001), vertical (10.0%, p < 0.0001), and resultant (9.8%, p < 0.0001) normalized peak foot forces. The significant interactions of climbing direction and rung spacing for vertical (p = 0.0010) and resultant (p = 0.0015) normalized peak foot forces further revealed that the effects of climbing direction were different between the two rung spacing conditions. The decreases in the vertical and resultant normalized peak foot forces, associated with reduced rung spacing, were higher for 356 mm rung spacing as compared to 305 mm rung spacing (11.3% vs 8.6% and 11.1% vs 8.4%) (Fig. 4). Significant effects of climbing direction for hand forces showed that climbing down

Table 3
ANOVA table for foot and hand force data.

	Foot Peak Force, Normalized				Hand Peak Force, Normalized			
	Horizon	Lateral	Vertical	Result	Horizon	Lateral	Vertical	Result
Sex								
Direction	*	**	**	**	**	**	**	**
Slope-Rail	**	**	**	**	**	**	**	**
Rung Spacing	**						*	*
Sex x Direction								
Sex x Slope-Rail	*				**	**		**
Sex x Rung S								
Direction x Slope-Rail	**	**	**	**	**	**	**	**
Direction x Rung S			*	*				
Slope-Rail x Rung S								

**p < 0.001; * 0.001 ≤ p ≤ 0.05.

Table 4
ANOVA table for joints moments data.

	Ankle Moment, Norm.			Hip Moment, Norm.			Shoulder Moment, Norm.		
	Front	Sagitt	Trans	Front	Sagitt	Trans	Front	Sagitt	Trans
Sex									
Direction									
Slope-Rail	**	**	**	**	**	**	**	**	**
Rung Spacing			*						
Sex x Direction									
Sex x Slope-Rail	*		**	**	**	**		**	*
Sex x Rung S									
Direction x Slope-Rail							*	*	
Direction x Rung S									
Slope-Rail x Rung S									

**p < 0.001; * 0.001 ≤ p ≤ 0.05.

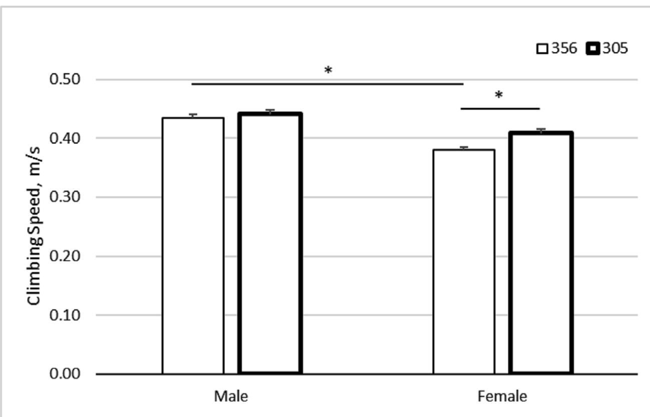


Fig. 3. Rung spacing and sex interaction on climbing speed.

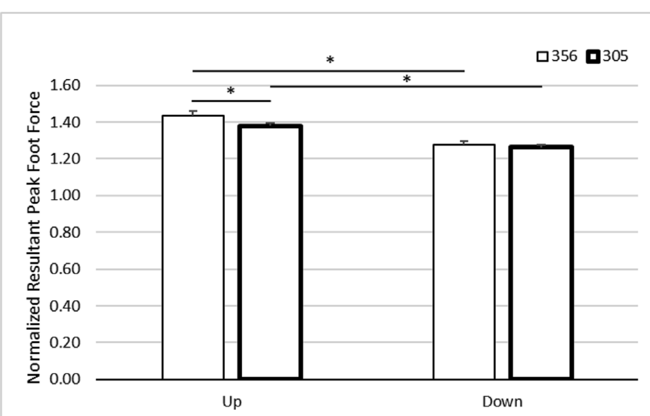


Fig. 4. Rung spacing and climbing direction interaction on normalized resultant peak foot force.

(descending) as compared to climbing up (ascending) was also associated with considerable increases in horizontal (50.9%, p < 0.0001), lateral (92.9%, p < 0.0001), vertical (49.8%, p < 0.0001), and resultant (47.8%, p < 0.0001) normalized peak hand forces.

3.3. Joint moments

Rung spacing: A significant effect of rung spacing demonstrated that reducing the rung spacing from 356 mm to 305 mm resulted in a 6.5% decrease (p = 0.0444) in ankle transverse moment (related to the lower-leg external rotation associated with the fixed-foot plantarflexion).

3.4. Ankle vertical overshoot

Rung spacing: A significant effect of rung spacing demonstrated that reducing the rung spacing from 356 mm to 305 mm resulted in a 13.8% increase (p < 0.0001) in ankle vertical overshoot. Furthermore, a significant interaction of rung-spacing with the slope-rail condition indicated that the increase effect was different for the different slope-rail conditions. Reduced rung spacing resulted in a consistent increase in ankle vertical overshoot for all conditions, which was more pronounced and significant for 30° low rail climbing (23.4% p < 0.0001) and 52.5° rung climbing (16.1% p = 0.0576) (Fig. 5).

Climbing direction: A significant effect of climbing direction showed that climbing down (descending) as compared to climbing up (ascending) resulted in a 29.9% decrease (p < 0.0001) of the ankle vertical overshoot.

3.5. Ankle horizontal moment arm

Climbing direction: A significant effect of climbing direction demonstrated that climbing down (descending) as compared to climbing up (ascending) resulted in a 7.6% increase (p = 0.0008) of ankle horizontal moment arm.

3.6. Relative foot contact time (as % of gait cycle)

Rung spacing: There was a significant (p = 0.0014) interaction of rung spacing with climbing direction on relative foot contact time. Reducing the rung spacing from 356 mm to 305 mm, resulted in a small increase (0.9%, p = 0.0301) of the relative foot contact time (as % of gait cycle) only in climbing down (descending) direction (Fig. 6).

Climbing direction: A significant effect of climbing direction demonstrated that climbing down (descending) as compared to climbing up (ascending) resulted in a 1.6% increase of the average foot force exertion worktime (as % of gait cycle). There was also a significant (p = 0.0014) interaction of climbing direction with rung spacing. Climbing down (descending) as compared to climbing up (ascending) resulted in significant increase (2.57%, p = 0.0025) of the average foot force exertion worktime only at 305 mm rung spacing (Fig. 6).

Correlation analysis revealed a moderate association between participants' sex and height but no significant association between participants' sex and weight (Table 1b). On average, male participants were 7.4 cm taller than the female participants as tested (with shoes) (Table 1a). There was also a strong association between height and weight among all participants (Table 1b).

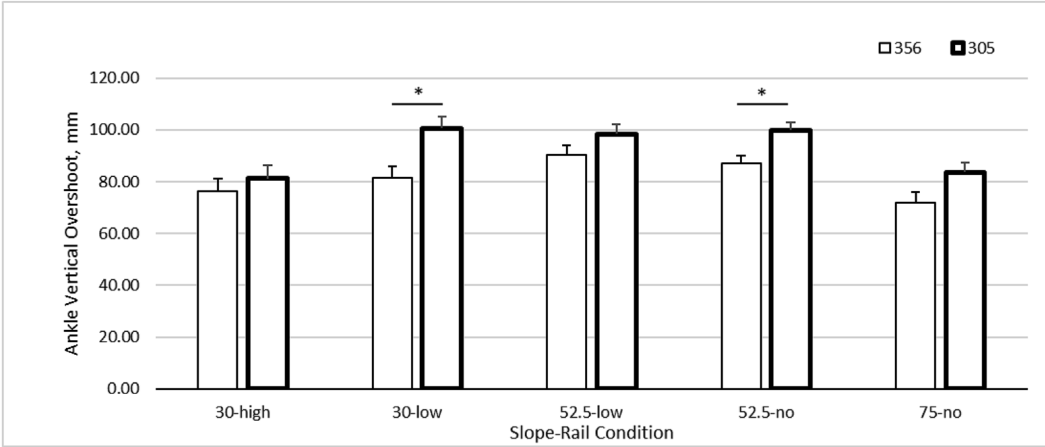


Fig. 5. Rung spacing and slope-rail interaction on ankle vertical overshoot.

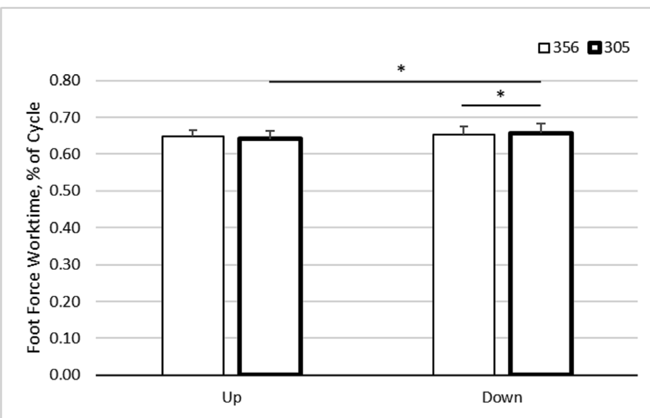


Fig. 6. Rung spacing and climbing direction interaction on foot force worktime (as % of gate cycle).

4. Discussion

4.1. Rung spacing effects

Reduced rung spacing (305 mm vs 356 mm) resulted in increased climbing speed (significant only for the female climbers), reduced resultant normalized peak hand forces, reduced resultant normalized peak foot forces in ascending, reduced ankle transverse moment, increased ankle overshoot, and increased relative foot contact time cycle in a downward direction.

The higher climbing speed associated with reduced rung spacing in this study indicates a more efficient climbing, specifically for the female climbers. Earlier research has demonstrated that hand-arm motion performance is optimized (and movement time is minimized) under ergonomically favorable conditions (Fitts, 1954), and this is also applicable for whole body movements during ladder climbing (Hammer and Shmaltz, 1992). Under this paradigm, the significant effect of rung spacing and its interaction with sex for climbing speed suggests that the reduced (305 mm) rung spacing may be an ergonomically more favorable condition specifically for female firefighters. Interestingly, the average increase of climbing speed (from 0.407 to 0.425 m/s) associated with the reduced rung spacing in this study was not accompanied by an increased biomechanical load; on the contrary, it was accomplished with reduced resultant normalized peak hand forces and foot forces in the ascending direction. This is in agreement with the Fitts' law paradigm and further highlights the efficiency of using the reduced rung spacing. This is also consistent with a study on vertical ladder climbing (Kamarajugadda, 2014), where the significant interactions between climbing speed (controlled at 1, 2, 3 s/step) and rung separation distance (254 mm, 305 mm, and 381 mm) for lower limb joint moments and muscle contractions, indicated that the existing rung separation (305 mm) used in wind towers is better than larger (381 mm) or shorter rung separations (254 mm). Furthermore, the self-selected climbing speed (0.323 m/s) for a 75° ladder slope with rung spacing at 255 mm reported by Dewar (1977) was lower than that for 356 mm rung spacing (0.353 m/s) and 305 mm rung spacing (0.376 m/s) for the same ladder slope in this study. These findings indicate that rung spacing of 305 mm may be optimal for climbing speed across different ladder user populations and climbing conditions.

The reduced rung spacing was associated with reduced biomechanical load (i.e., lower forces and moments). The increased hand forces with increased rung spacing in this study is consistent with the findings of McIntyre and Bates (1982) which indicated that with increases in the rung spacing there was a corresponding increased use of the hands for providing propulsive forces. The rung spacing effects on hand and foot forces in this study are also compatible with the results of Bloswick and Chaffin (1990). They studied the effect of rung spacing (305 mm and 381 mm), climbing speed (0.305 m/s, 0.508 m/s), and climbing direction at different ladder slopes (70°, 75° 80°, and 90°) on their potential contribution to slip/falls and low back overexertion hazards. Their results indicated significant effects of rung spacing on vertical and resultant foot force ($p < 0.1$), and vertical hand force ($p < 0.001$). However, the rung spacing effects, (together with climbing speed, and climbing direction effects) were considered as not important since they explained only about 1% of the variation in hand and foot forces and were not discussed in greater detail in the Bloswick and Chaffin (1990) paper. More recently, Kamarajugadda (2014) also found that an increase in rung spacing (305 mm–380 mm) significantly increased the horizontal foot force during rung climbing of a vertical ladder and this effect was stronger for medium-height male and shorter female subjects.

The finding of reduced ankle transverse moment with reduced rung spacing from 356 mm to 305 mm in this study is in agreement with the results of Hoozemans et al. (2005) who analyzed the effect of rung spacing (300 mm and 350 mm) on maximum total moments at the hip, knee, and ankle joint while ascending and descending ladders at an inclination of 77°. The study concluded that for the mechanical load, the 300 mm rung separation is preferable (i.e., lower). Mechanistically, the increase of ankle transverse moment with increased rung spacing can be interpreted as resulting from the increased external rotation of the lower leg associated with the increased propulsive vertical trust from the ankle in the ankle "push-up" phase. An ankle "push-up" phase has been suggested to recognize the role of the plantarflexors as a contributor to upward acceleration during the period of double limb support in stair climbing (Wilken et al., 2011). The "push-up" phase motion at the ankle (and subtalar) joint can be described as a closed-chain (fixed-foot) plantarflexion which is accompanied and accomplished by external rotation of the lower leg.

The increased ankle overshoot associated with decreased rung spacing (305 mm vs 356 mm) in this study may indicate a decreased risk of tripping when stepping up to the next rung. Furthermore, the slope/rail and rung-spacing interaction indicates that this effect may be more pronounced at lower ladder angles and for lower rail/rung holding conditions. Fatigue associated with firefighting activities have been found to reduce foot clearance during stair ascent, thus increasing the risk of tripping (Kesler et al., 2016). A reduced rung spacing on aerial firetruck ladders may compensate for the increased tripping risk associated with firefighting-related fatigue. Nevertheless, the over-stepping associated with excessive ankle overshot under certain climbing conditions, while still safer for tripping, may affect limb contact dynamics and develop fatigue and thus be interpreted as less efficient.

The increase in relative foot contact time for descending associated with the reduced rung spacing (305 mm vs 356 mm) in this study was relatively small (0.9%), but it may indicate improved movement efficiency, i.e., reduced relative time for leg movement to establish new foot contact. As noted earlier, the more efficient climbing with the reduced rung spacing was characterized with increased climbing speed (only significant for females). This inference is consistent with the study of Dewar (1977), which demonstrated a tendency of increased relative contact time (as % of gait cycle) with increasing climbing speed.

4.2. Climbing direction effects

Climbing down as compared to climbing up resulted in a decrease in normalized resultant foot forces, climbing speed, and ankle vertical overshoot. It was also associated with increase of relative foot contact time for the 305 mm rung spacing, horizontal moment arm at the ankle, normalized horizontal foot forces and normalized resultant hand forces.

The finding of slower speed for descending in this study is consistent with the study of Hammer and Shmalz, (1992) which found longer times for descending versus ascending across a range of ladder slopes. The slower speed in descending may be related to the increased complexity of the task of climbing down versus climbing up. Previous studies in walking have shown that people walk slower and use a shorter stride in a backward direction as compared to forward direction (Grasso et al., 1998). In walking, vision is critical when the subject is uncertain about their foot placement. It can be hard to see where the foot is being placed for both walking backward and descending a ladder. From the literature it appears that during ladder climbing the chance for a fall to occur is greater during a descent than an ascent (Lee and Tung, 1992; McIntyre, 1979; Pliner et al., 2017). The slower and more careful movements in descending a ladder may also be a behavioral strategy to prevent a fall.

The decrease in normalized resultant foot forces in this study indicates more cautious movements, most likely also due to the uncertainty in the foot placement while moving backwards. Moving the feet and hands to the next rung can be characterized as a Fitts task (Hoffmann, 1991); stepping downward away from the body requires more time and control then stepping up close to the body. The reduced forces at the foot in descending may be associated with a strategy to reduce the risk of slipping on a rung. During descent, the momentum is in the same direction as gravity leading to higher risk of a fall if a contact point is lost – thus people may utilize a more cautious strategy (Pliner et al., 2017). It has been reported that during descent the hip moments are larger while the ankle and knee moments are smaller than for ascent (Kamarajugadda, 2014). Furthermore, during descent, climbers may shift more of their weight to their hands to gain better control of feet positioning. The considerable increase (~50%) in normalized resultant hand forces in descending over ascending in this study suggest that climbers were supporting their body with their arms as they lower their feet to the next rung. The larger horizontal foot forces in descending were mostly due to the large effects at some of the low-slope and rail holding (30°-high and 52.5°-low) conditions, which may be why these results are not consistent with previous reports of “no effect” of climbing direction at steeper ladder angles with rung climbing (Bloswick and Chaffin, 1990).

The lower ankle vertical overshoot in descending is a result of a more efficient downward foot movement behavior. When stepping up, it is necessary to lift the ankle high enough to clear the rung, but stepping down can be achieved by only sliding the foot off from the rung. The increase of the horizontal moment arm at the ankle is consistent with a more cautious movement strategy as noted above. The more forward contact position of the foot allows for larger rotational movement to better cushion the landing. However, it may be associated with increased risk of slipping (Pliner et al., 2014). In this study, there were nine instances in which participants bumped a rung, a foot slipped or there were additional movements to establish control between the foot and the rung; six of those nine cases (including three male and three female participants) involved stepping down. The increase of relative foot contact time only for the 305 mm rung spacing may indicate improved movement efficiency as noted above, i.e., reduced relative time for leg movement to establish new foot contact for the smaller rung spacing.

While the study was not conceived with the goal of studying the effects of ladder climbing direction, the findings suggest that descending is more complex and climbers maybe at greater fall risk when descending than when ascending. Even small, the effects of rung spacing on foot movements during descent may be critical to safety.

4.3. Participant sex effects

Overall female climbers were 10% slower than male climbers; however, the effect was significant (with a difference of 12.5%) only for the 356 mm rung spacing. It has been previously shown (Dewar, 1977) that shorter subjects have to flex hips and knees more to lift their feet onto a rung. It is likely that the generally shorter female participants required greater upper and lower limb range-of-motion than the taller male participants to reach the same rungs – and as a result, at the larger rung spacing, the females had to slow down considerably more than at the smaller rung spacing. Livingston et al. (1991) noted that subjects appear to adjust to different stair dimensions by varying the flexion and extension at the knee rather than at the ankle or hip. They also found that subject height was an important factor in determining knee motion during stair climbing – shorter subjects had larger knee flexion angles, whereas taller subjects had smaller knee flexion angles. These results also highlight the potential benefit of the reduced rung spacing for female climbers and to reduce climbing speed disparity across sexes.

4.4. Limitations

Limitations of the study include the limited length of the ladder in the experimental setup, the random sample of the participants, the non-standardized boots used by the participants, and the correlation between sex and height.

While the participants were experienced ladder climbers, each trial was based on only eight ascents and descents of the ladder. The length of the ladder only permitted them to complete three or four steps before coming to a stop. It is unlikely that the subjects were able to achieve the same kind of steady state rhythm that they would if they were climbing a longer ladder. However, any effects of the short trials should be consistent across all of the treatments. Also, it should not be assumed that firefighters only climb long ladders. Short ladders are also routinely used.

The participants were a random sample from the local firefighter community which may not adequately reflect the physical characteristics of the US firefighters. In fact, the male study participants were on average 1.9 cm shorter and 10 kg lighter, while the female study participants were on average 1.0 cm taller and 2 kg heavier than the published US firefighter population average anthropometric values (Hsiao et al., 2014). Thus, the sex differences for average height and average weight in this study were lower (7.3 cm and 8.6 kg) as compared to the US firefighter population (10.2 cm and 20.8 kg), suggesting that some of the sex effects on ladder climbing biomechanics in this study may be under-estimated.

The boots worn by the firefighter participants were those that they use when fighting fires. The boots were quite heavy and the styles varied among participants. The boots made it difficult to see the markers on the ankles and were a likely cause of statistical noise.

Sex and height were correlated (Table 1b) and it is not possible to completely separate the differences in their effects. Further analysis using participants' height instead of sex as an independent variable did not reveal any significant height-rung spacing interactions. Normalizing the force and moment results by weight accounted for the potential effects of body mass. A larger study group with a broader range of weights and heights for both males and females would help determine if there is an effect of sex beyond that of height and weight.

Even though the participants paused at the top and bottom of the ladder during each trial, and in between trials, it can be argued that there is a fatigue bias in the data. Plots and simple regression analyses were performed to determine if there were any significant changes in horizontal ankle-rung distance, overshoot or climbing speed from the beginning to the end of the experiment. No evidence of fatigue was identified.

5. Conclusions

A reduced rung spacing on fire-truck aerial ladders, from 356 mm to 305 mm, may be more ergonomically compatible to firefighters and especially beneficial to female firefighters. The 305 mm rung spacing was associated with an increase in climbing speed for the female participants indicating improved climbing efficiency; lower resultant hand and foot forces and ankle transverse moment suggesting reduced biomechanical stress; and increased ankle vertical overshoot indicating a reduced risk of tripping. While the reported effects during a short period of climbing were relatively small, they can be impactful for improving climbing efficiency, reducing fatigue, and enhancing the safety of firefighters on long climbs which are typical for firefighting and rescue operations with aerial ladders.

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.

Acknowledgement

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 was completed by the University of Michigan. The final data analysis and interpretation were led and completed by NIOSH. 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.

Appendix A

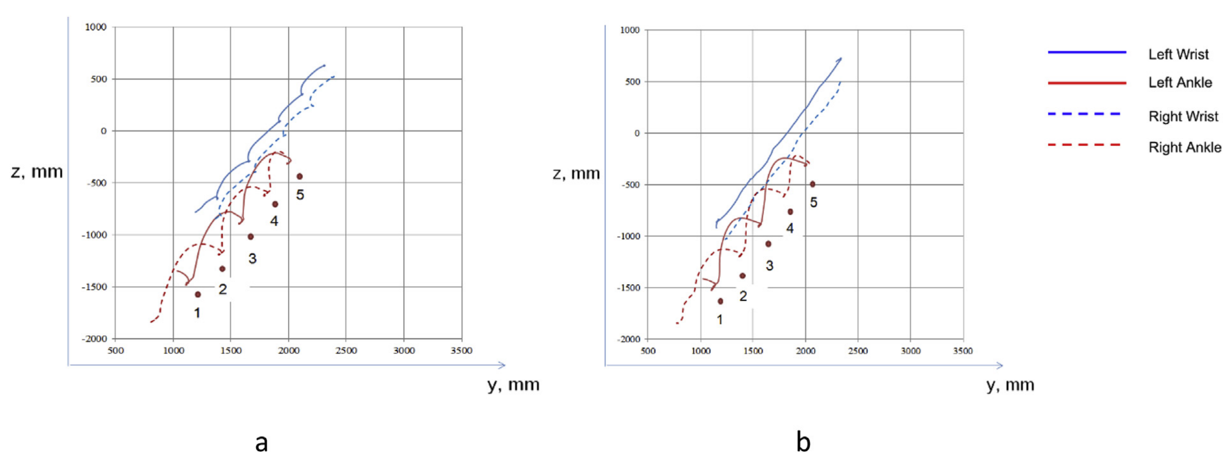
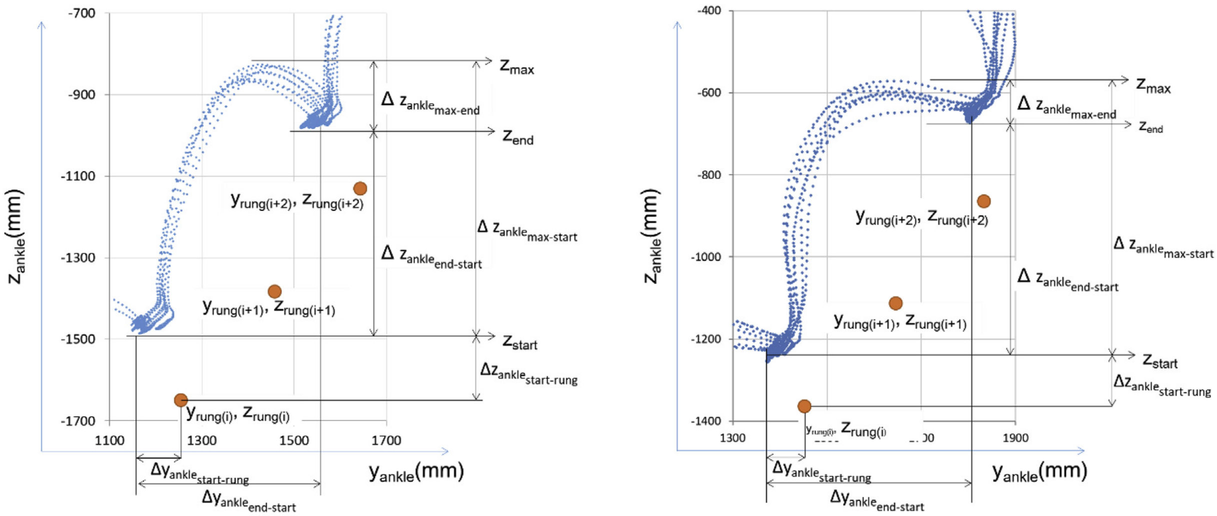


Fig. A1. Wrist and ankle movements for participant #14 (female, 173.0 cm, 83.0 Kg) ascending (a) and descending (b) a ladder with 356 mm rung spacing at slope 52.5°, using "low" 305 mm rails.



a b

Fig. A2. Typical ankle trajectories (participant #4, male, 177.5 cm, 84.8 kg) for (a) ascending and (b) descending on a ladder with 305 mm rung spacing at 52.5° slope and "low" 305 mm rails. In ascending, the ankle appears to rotate forward before lifting off from the rung and then ascends to a local maximum height before settling down and back as the foot comes to rest on the next rung.

$\Delta y_{anklestart\text{-}rung}$ - ankle horizontal moment arm (distance between the horizontal position of the ankle and the rung)
$\Delta z_{anklemax\text{-}end}$ -vertical overshoot (distance between the ankle height local maximum and ankle height at step end)

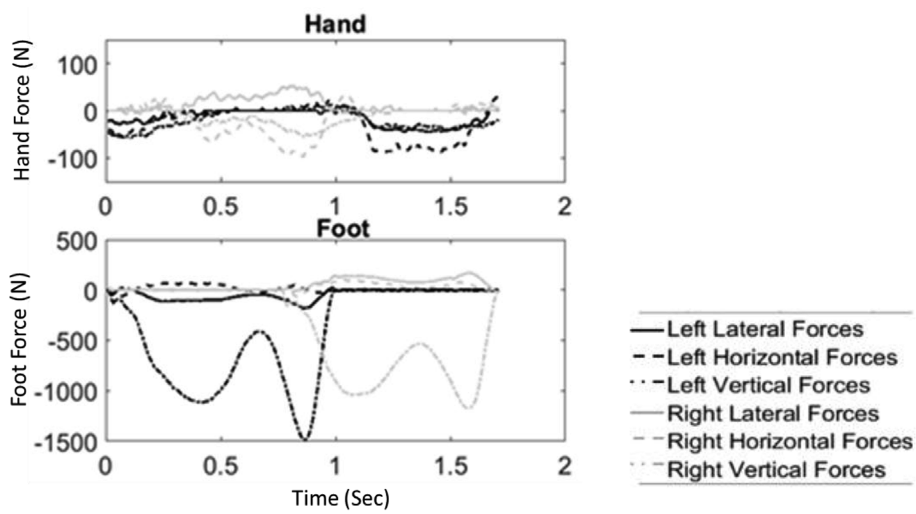
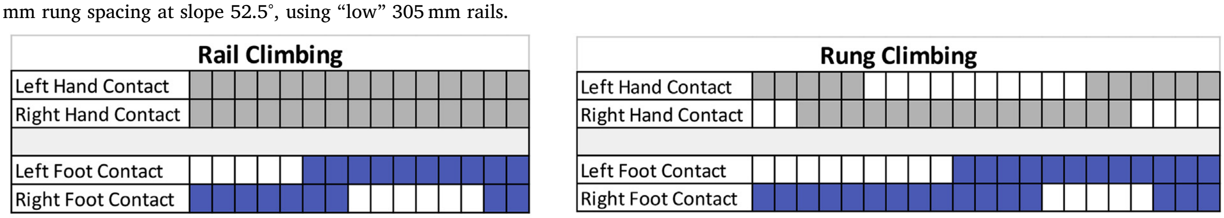


Fig. A3. Sample hand and foot forces (N), along the x, y and z axes versus time (s), for two ascending steps by participant #4 (male, 177.5 cm, 84.8 kg) on a ladder with 356 mm rung spacing at slope 52.5°, using "low" 305 mm rails.



a b

Fig. A4. Temporal relationship between hand and foot forces for rung and rail climbing at ladder slope 52.5° for participant #4 (male, 177.5 cm, 84.8 kg), 356 mm rung spacing, and ascending/descending pooled.

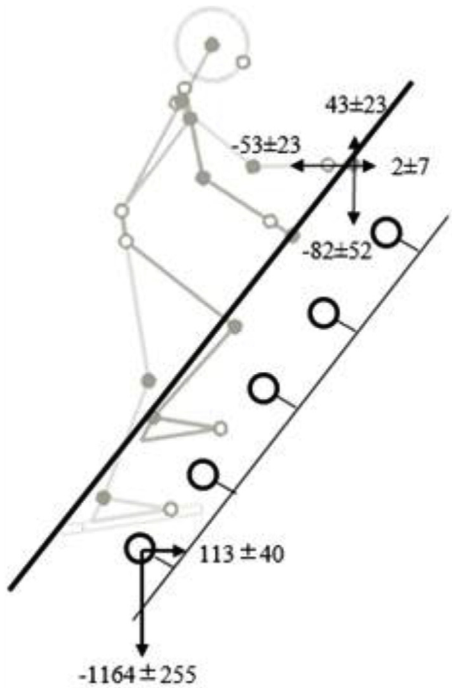


Fig. A5. Horizontal and vertical hand and foot forces at slope 52.5°, using "low" 305 mm rails, with all 19 subjects pooled, 305 mm and 356 mm rung spacing pooled, ascending and descending pooled.

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