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# Effects of extension ladder fly configuration on climbing safety

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ABSTRACT

Fall injuries often occur on extension ladders. The extendable fly section of an extension ladder is typically closer to the user than the base section, though this design is minimally justified. This study investigates the effects of reversing the fly on foot placement, frictional requirements, adverse stepping events (repositioning the foot or kicking the rung), and user preferences. Participant foot placement was farther posterior (rung contacted nearer to toes) in the traditional ladder compared to the reversed fly condition during descent, with farther anterior foot placements during ascent. The reversed configuration had similar friction requirements during early/mid stance and significantly lower frictional requirements during late stance. Increased friction requirements during late stance were associated with farther anterior foot placement and further plantar flexed foot orientation. The reversed fly had 5 adverse stepping events versus 22 that occurred in the traditional configuration. Users typically preferred the reversed fly. These results suggest that a reversed extension ladder configuration offers potential benefits in reducing fall-related injuries that should motivate future research and development work.

## 1. Introduction

Falls involving ladders are a critical concern in both occupational and non-occupational settings. In 2020, there was a total of 22,710 occupational ladder injuries with 85% of these resulting from falls (U.S. Bureau of Labor Statistics, 2023). Ladder falls are particularly dangerous as 43% of fatal falls in the last decade involved ladders (Melmer et al., 2020). Outside of fatal incidents, 22% of ladder falls have been categorized as serious injuries, with 14% requiring hospital stays longer than a week (Vallmuur et al., 2016). Approximately 80% of hospitalizations for ladder related falls were non-occupational in nature (Vallmuur et al., 2016). Injuries from falls occur 2–4 times more often during ladder descent than ascent (Cabilan et al., 2018; Lombardi et al., 2011; Rapp van Roden et al., 2021), indicating that this half of the climbing cycle holds an increased risk for ladder falls.

Extension ladders account for 30% of occupational ladder accidents (Cohen and Lin, 1991) and 25% of ladder falls that result in emergency department visits (Cabilan et al., 2018). Extension ladder falls frequently occur at heights greater than 10 feet (Lombardi et al., 2011), which can make these ladders more dangerous as increased fall height and increased injury risk are correlated (Alizo et al., 2018; Aneziris et al., 2008; Lombardi et al., 2011). One feature of extension ladders that may make them more dangerous is the transition between ladder sections. The fly or upper section is typically stacked on top of the lower base section, necessitating a transition between the sections. This typical configuration results in users having to shift their foot placement posteriorly while ascending and anteriorly while descending. This transition between sections has been found to be associated with both slips and missteps (Cohen and Lin, 1991), some resulting in fatal accidents (National Institute for Occupational Safety and Health, 1998).

One alternative design to the traditional fly configuration is a reversed fly configuration which stacks the fly section underneath the base section, away from the climber (Fig. 1B). While less common, this design can be found on the market with manufacturers claiming that the reversed sections allows "… for a safer descent" (Tivoli, 2024). Extension ladder safety codes from the American National Standards Institute and the National Fire Protection Association allow for the fly being located either in front of or to the rear of the base section (American National Standards Institute, 2017; National Fire Protection Association, 2020a; National Fire Protection Association, 2020b), indicating that both designs can meet manufacturing safety standards. The reversed fly configuration is also recommended by some major fire departments as a method of increasing firefighter safety during ladder descent (Seattle Fire Department, 2024), though it is recommended to do this only with ladders designed for this configuration, rather than modifying the use of a traditional extension ladder (National Fire Protection Association, 2020b). While there is precedent for extension ladders designed with a reversed fly configuration, its impact on climbing biomechanics in the

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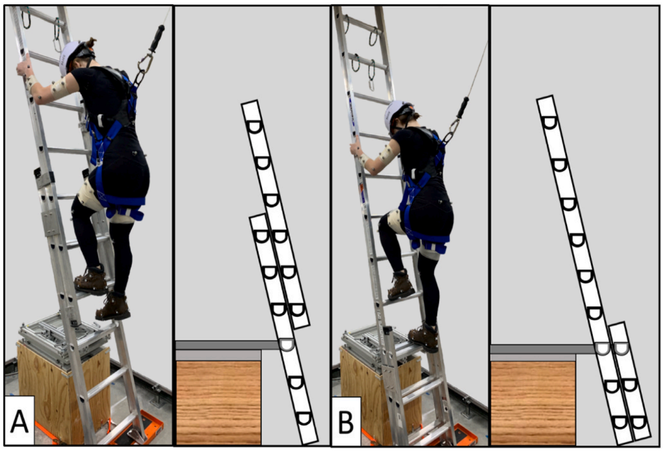


**Fig. 1.** Extension ladder descent in **A)** a traditional extension ladder fly configuration and **B)** a reversed extension ladder fly configuration. The third rung of each ladder was attached to a force plate that measured the shoe-rung forces.

context of fall risk has yet to be examined.

Slips and missteps are a common initiating event for ladder falls causing 33% of ladder fall accidents (based on data that includes but is not limited to extension ladders) (Cohen and Lin, 1991). Foot placement is a biomechanical factor that has been associated with misstep risk, and adverse stepping events. Previous work which focused on stepping up on to a curb found that foot placement closer to the surface edge was associated with loss of balance events (Elliott and Chapman, 2010; Johnson et al., 2013). In ladder climbing, further posterior foot placements (i.e. rung closer to toe) have been found to contribute to missed rung contact or slips following a rung perturbation (Pliner, 2020). Further posterior foot placements are also associated with increased slipping risk (Martin et al., 2020; Pliner et al., 2014).

The required coefficient of friction (RCOF) is one metric that can help explain the slip risk at the extension ladder transition. RCOF quantifies the friction required between contact surfaces to avoid a slip. Traditionally, RCOF has been analyzed as the peak ratio between the shear and normal forces during foot contact, to represent the risk of a slip occurrence both in level walking (Beschorner et al., 2016; Chang et al., 2011, 2012; Durá et al., 2005; Iraqi et al., 2018; Kim et al., 2005) and ladder climbing (Griffin et al., 2023; Martin et al., 2020). While previous work has examined ladder climbing and RCOF in respect to ladder ascent (Martin et al., 2020), there have not yet been any studies addressing the impact of extension ladder fly positioning on RCOF during ladder descent.

Body kinematics have been explored as a factor that impacts slip risk and frictional requirements. Previous studies have examined the relationship to slip risk for both whole-body kinematics (Bloswick and Chaffin, 1990; Griffin et al., 2023; Lee et al., 1994; Martin et al., 2020) and foot kinematics (Griffin et al., 2023; Martin et al., 2020; Pliner et al., 2014) during ladder climbing. Foot position on the rung (Pliner et al., 2014) and foot angle (Griffin et al., 2023; Martin et al., 2020; Pliner et al., 2014) have been found to be related to slip risk and these metrics may help explain RCOF variations in ladder fly transitions.

The purpose of this study was to quantify the impact of extension ladder fly positioning on climbing. Climbing safety was investigated through multiple metrics that are relevant to safety on ladders such as foot placement, frictional requirements, and adverse stepping events. With our testing apparatus, we were able to collect foot kinematics for ascending and descending climbs and rung kinetics for descending climbs only. We hypothesized that a reversal of the traditional extension ladder fly positioning would result in farther anterior foot placements when descending and farther posterior foot placements when ascending compared to a traditional extension ladder. We also hypothesized that a reversal of the traditional extension ladder fly positioning would be associated with decreased RCOF values during ladder descent. Foot kinematics (i.e., foot angle and placement) were investigated to determine their relationship to RCOF during extension ladder climbing. We hypothesized that farther posterior and more dorsiflexed (toe-up) foot placements would be associated with increased RCOF values. Finally, this study characterized adverse stepping events and examined the role of foot placement on foot readjustments during ladder climbing. There was no hypothesis for these adverse events as there was no pre-existing knowledge to suggest more adverse events in a specific configuration.

## 2. Methods

### 2.1. Participants

Twenty participants (10 female, 10 male; 36.4 ± 16.1 years; 170.3 ± 87.8 cm; 26.7 ± 4.1 kg/m$^2$) enrolled in this study. Participants were eligible to take part in the study if they were 18–65 years of age, had climbed ladders at least 4 times in the past year, were under 136 kg (due to harness system restrictions), had a height less than 196 cm (due to space restrictions), and were free of self-reported musculoskeletal disorders, neurological disorders, balance problems, and recent injuries. Ethical approval was obtained from the University of Pittsburgh Institutional Review Board (Study #19100204) and all participants provided informed consent. This research was performed in accordance with the Declaration of Helsinki of 1975.

### 2.2. Procedure

Two ladder configurations were used: a traditional extension ladder with the fly section stacked on top of the base section, towards the participant (Fig. 1A) and a reversed extension ladder in which the fly section was stacked underneath the base section, away from the participant (Fig. 1B). Each configuration was placed at an angle of 75.5° from horizontal (Chang et al., 2004, 2005; Simeonov and Webb, 2017). The 3rd rung of each configuration was attached to a force plate (AMTI Inc., Watertown, MA, USA: 1080 Hz) and 12 motion tracking cameras (Vicon T40s, Vicon Motion Systems Ltd., Centennial, CO, USA: 120 Hz) collected kinematic data that was time-synced to the kinetic data from the force plate. The force plate was mounted to concrete blocks to minimize signal artifacts in the force data. Seventy-nine reflective markers were secured to anatomical landmarks (Moyer, 2006) and participants were outfitted with athletic wear and a safety harness attached to a fall arrest system (Self Retracting Lanyard, Ropes Park Equipment, Fairfield, CT, USA). Markers of interest include those placed on the medial and lateral sides of the heel, directly inferior of the medial and lateral malleoli, and on medial and lateral portions of the toes (Moyer, 2006). The participants were asked to wear the shoes they would typically use to climb ladders. Participants height and weight were recorded at the beginning of testing without shoes and equipment.

Participants were instructed to climb to the fifth rung of a ladder where they moved a carabiner from one rope loop to another before descending down to the ground. Participants were asked to complete this at a comfortable but urgent pace, similar to a pace they would employ during a workday. Three repeated trials were collected in each configuration with the configuration order randomized. Prior to each condition, participants were given time to practice climbing up and down the ladder.

### 2.3. Data analysis

The data analyses for this study focused on foot placement (Anterior/Posterior [AP] foot contact relative to the rung), frictional requirements (peak RCOF and root mean squared RCOF), foot orientation (foot angle with respect to horizontal), adverse events (categorized stepping events), and user preference.

Foot placement was calculated at the onset of the stance phase, occurring when the participant's foot first contacted the force rung (Fig. 2B). The foot position data was filtered using a 7th order Butterworth filter with a 10 Hz cutoff. This metric was quantified as a percentage of foot length (AP distance between Medial Front Foot and Inferior Heel markers) where a higher value indicates the foot contacting the rung closer to the heel while a lower percentage indicates the foot contacting the rung closer to the toe (i.e., 50% indicating rung contact with the center of the foot and 0% indicating rung contact with the end of the first phalange). Foot placement was calculated for both ascent and descent, with ascending foot placement occurring at the rung above the force rung (ascending transition) and descending foot placement occurring at the force rung (descending transition). Along with foot placement, foot orientation was captured by the foot angle at the time of RCOF during ladder descents. Foot angle was with respect to horizontal. A positive angle indicates that the foot is in dorsiflexion (toe up) while a negative angle indicates that the foot is in plantar flexion (toe down).

Only descending trials were evaluated in the RCOF analysis. The rung force and body position data were filtered using 9th and 7th order Butterworth filters with 35 Hz and 10 Hz cutoffs, respectively. RCOF was calculated using the rung reaction forces transformed into the local foot coordination system (Fig. 2A) (See Supplementary Materials) (Griffin et al., 2023; Martin et al., 2020). RCOF was measured as the ratio of the resultant shear to normal forces in the foot coordinate system.

The shoe-rung contact period was defined as three separate phases: 1) the initial contact period, 2) the first half of stance after the initial contact period, and 3) the second half of stance (Fig. 3). The initial contact period started at initial foot contact with the force rung and continued until the 3rd RCOF peak occurred. The stance period started after this initial contact phase and continued until toe off. Stance was divided, temporally, into the first and second halves.

The analysis for the first stage of stance focused on RCOF peaks. A cluster analysis was performed on the data set to determine the different peak groupings present in the trials (See Supplementary Materials). Cluster analysis was implemented since it provides an objective pattern recognition method that can sort a dataset into groups containing datapoints with similar values. Peaks were separated into three groups based upon the cluster analysis, referred to as Group A, Group B, or Group C (Fig. 3).

For the second and third phases of stance, RCOF was characterized using the root mean square (RMS) of the time-series data. RMS RCOF was chosen instead of the typically utilized RCOF peak values (Chang et al., 2005; Griffin et al., 2023; Martin et al., 2020; Simeonov et al., 2017) to account for shoe-rung contact region variability. Peak RCOF values are typically chosen as the highest slip risk during climbing or walking based upon the implicit assumption of constant ACOF. ACOF may be dependent upon the contact surface between the climber's shoe and the ladder rung and therefore may vary across stance as the shoe/rung contact region changes. With a potentially varying ACOF, it becomes less clear that an RCOF peak is the highest slip risk and using a method to characterize friction requirements over time is useful. In our analysis, we chose to use a new metric of RMS RCOF for these phases

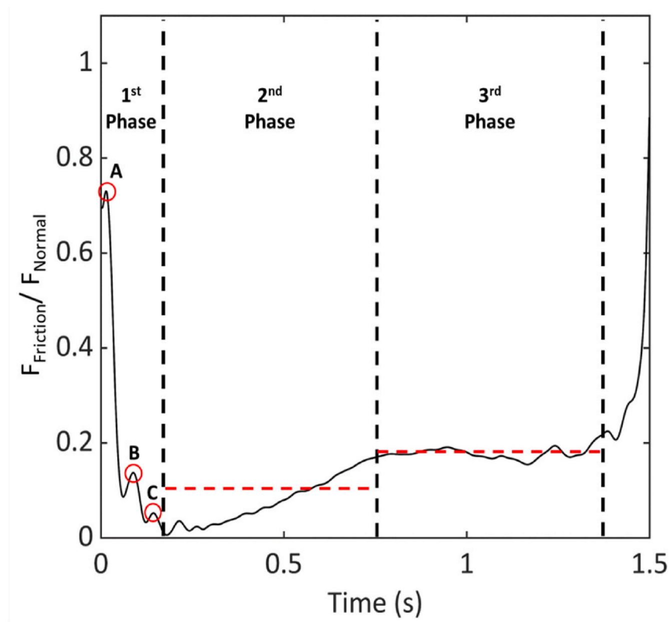


**Fig. 3.** Time series plot of the ratio of frictional and normal forces through a descent trial with the three phases. The three RCOF peaks (A, B, C) are located within phase 1. RMS RCOF values in phases 2 and 3 are indicated by red dashed lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

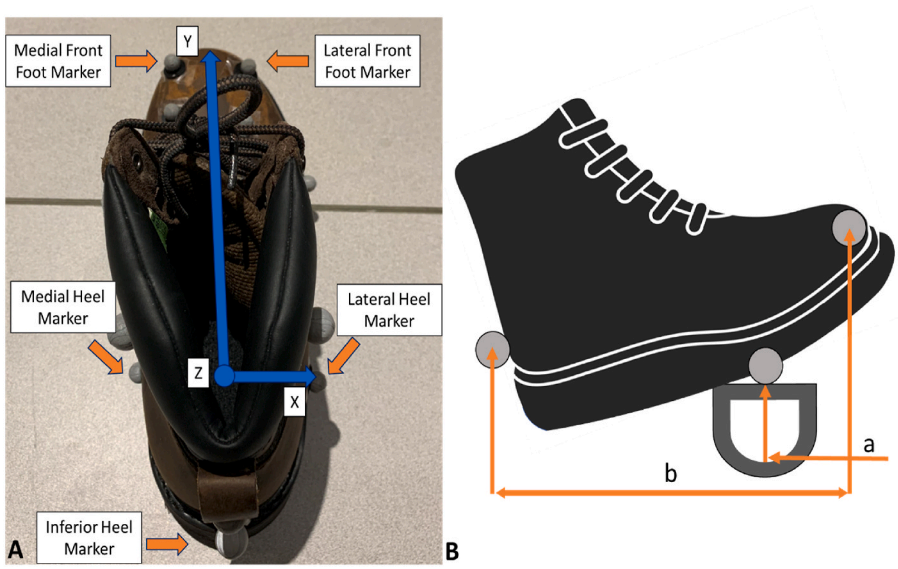


**Fig. 2. A)** Foot local coordinate system with the markers of interest labelled. **B)** Foot position is defined as the anterior-posterior distance between the front foot and rung markers (a) divided by the foot length (distance between the front foot and inferior heel markers) (b) where *Foot Position* $= \left(\frac{a}{b}\right) * 100$.

since it allows for aggregating time-series values while weighting the results to its larger values. The RMS RCOF of each participant for second and third phases of stance were averaged between the replicates for each condition.

Adverse stepping events were also characterized in this study. After observing cases where participants shifted their foot after contact, trials where a participant had some type of adverse event related to stepping were counted including: readjusting their foot on the rung prior to the transition step, readjusting their foot after the transition step, and kicking a rung when negotiating the transition. Foot readjustments are a circumstance where the participant is uncomfortable with their initial foot placement and was therefore interpreted as being related to misstep risk. Kicking the rung is a disruption of the swing phase, likely due to the transition between sections impeding their typical swing path. These events were identified based on observation of motion tracking videos conducted by 2 reviewers on all the trials (reviewers reached consensus for all trials). After all extension ladder climbing trials, participants were asked for their preferred extension ladder configuration to measure preference (traditional, reversed, or no preference).

### 2.4. Statistical analysis

Paired t-tests were used to compare the foot placement values between the two ladder configurations. Descending foot placement values and ascending foot placement values were analyzed separately. Paired t-tests were used to compare the peak RCOF values between the two ladder configurations. Peak A values were compared between the configurations for one statistical test while a combination of Peaks B and C were used for analysis in the second statistical test. For this second test, the higher average value between Type B and C was selected for each trial due to overlap in these clusters. The averaged RMS RCOF values were analyzed using paired t-tests comparing between the ladder configurations for the second and third phases of stance. The difference in adverse stepping events between configurations was tested with a two-sample z test of proportions.

Any part of stance that was found to have a significant difference between configurations for RCOF was then analyzed in a post-hoc analysis to identify which biomechanical variables might explain the effect. In this post-hoc analysis, two linear bivariate regressions were performed with RCOF as the dependent variable and foot position and foot angle as independent variables. Non-parametric regression models (Spearman correlation) (foot angle on third phase RMS RCOF) were utilized if needed to meet test assumptions. The impact of foot placements on foot readjustments was evaluated with a logistic regression analysis, only if the minimum number of events were found in that climbing direction to meet the test assumptions (>5 events and non-events).

## 3. Results

### 3.1. The effect of ladder configuration on safety outcome metrics

Ladder configuration impacted foot placement during both ascending and descending. More anterior foot placements relative to the rung were observed in the reversed configuration than the traditional configuration ($t_{16} = 7.7$; $p < 0.001$) (Fig. 4) when descending the ladder. The reversed configuration had an average foot placement of 49.2% (near midfoot) compared to 23.8% (near the ball of the foot) in the traditional configuration. More posterior foot placements relative to the rung were observed in the reversed configuration than the traditional configuration ($t_{18} = 4.4$; $p < 0.001$) (Fig. 5) when ascending the ladder. The reversed configuration was found to have an average foot placement of 21.7% (near the ball of the foot) compared to the 33.4% (near midpoint of midfoot and the ball of the foot) average foot placement in the traditional configuration. Therefore, the reversed fly configuration led to foot placement nearer to the toes during ascent but nearer to the midfoot during descent. Importantly, the difference was more pronounced during descent (~25% foot length) than during ascent (~10% foot length).

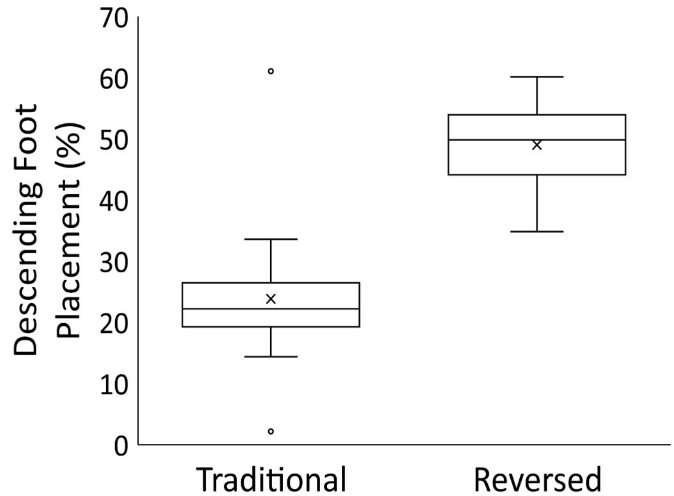


**Fig. 4.** Descending foot placement values for traditional and reversed fly configurations, with higher values indicating farther anterior foot placement relative to the rung, where X signifies the mean, the horizontal lines indicate the median and quartiles, and the circles indicate points that deviate more than 1.5 times the interquartile range from the nearest quartile.

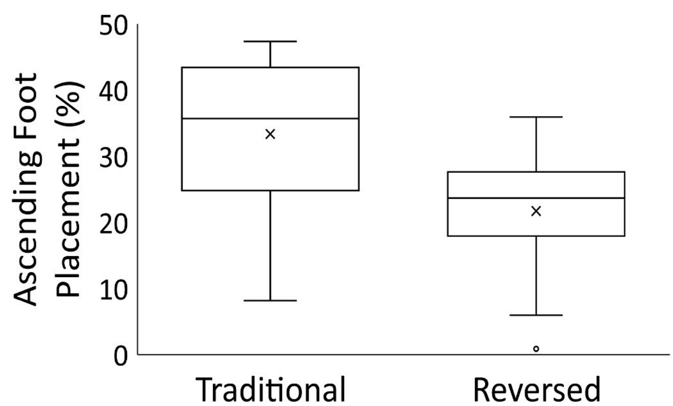


**Fig. 5.** Ascending foot placement values for traditional and reversed fly configurations, with higher values indicating farther anterior foot placement relative to the rung, where X signifies the mean, the horizontal lines indicate the median and quartiles, and the circles indicate points that deviate more than 1.5 times the interquartile range from the nearest quartile.

The RCOF values were compared between the ladder conditions within the three peak groups. Thirteen participants had Group A peaks in both ladder configurations and seventeen participants had Group B/C peaks in both conditions. No significant differences were found between the ladder conditions in the Group A peaks ($t_{12} = 1.63$; $p = 0.13$) or the Group B/C peaks ($t_{16} = 0.94$; $p = 0.36$). There was no significant difference in the RMS RCOF between the ladder configurations for the second phase of stance ($t_{15} = 0.80$; $p = 0.44$). There was a significant difference in the third phase of stance for RMS RCOF ($t_{15} = 3.01$; $p = 0.01$) with higher RMS RCOF values in the traditional fly configuration (Fig. 6).

A total of 27 adverse stepping events were observed, with 22 (18% of trials collected) occurring in the traditional configuration and 5 (4% of trials collected) in the reversed configuration ($z = 3.47$; $p < 0.001$) (Table 1). One participant accounted for 10 adverse stepping events and at least one adverse stepping event was observed for 9 participants. A total of 16 events occurred during ladder ascent while the remaining 11

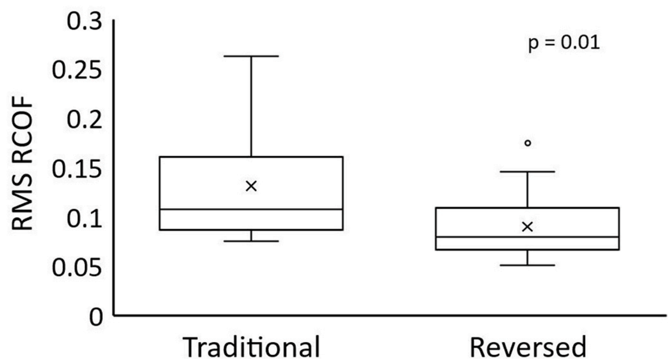


**Fig. 6.** RMS RCOF values for traditional and reversed fly configurations in the third phase of stance where X signifies the mean, the horizontal lines indicate the median and quartiles, and the circles indicate points that deviate more than 1.5 times the interquartile range from nearest quartile.

**Table 1**
Distribution of the adverse stepping events between climbing direction, event, and configuration. Readjustment events refer to a readjustment of foot position and before/after refers to the transition rung.

| Event | Traditional | Reversed | Both |
|---|---|---|---|
| Ascending | | | |
| Readjustment Before | 6 | 0 | 6 |
| Readjustment After | 1 | 3 | 4 |
| Kicked Rung | 5 | 1 | 6 |
| Descending | | | |
| Readjustment Before | 3 | 1 | 4 |
| Readjustment After | 7 | 0 | 7 |
| Kicked Rung | 0 | 0 | 0 |
| Total ASEs | 22 | 5 | 27 |

occurred during ladder descents. 16 of 20 participants stated a preference for the reversed fly configuration, 3 participants had no preference for either configuration, and 1 participant expressed a preference for the traditional configuration.

### *3.2. Relationships across safety outcome metrics and foot biomechanics metrics*

The relationships between RMS RCOF in the third phase of stance and the foot position and foot angle were investigated. This RMS RCOF was significantly related to foot position ($F_{1,32} = 20.4$; $p < 0.001$) (Fig. 7). This relationship accounted for 39% of the variability in third phase RMS RCOF. Increasing the foot position from the first to third quartile leads to a decrease of 0.06 in RCOF. A significant negative correlation was observed between foot angle and third phase RMS RCOF ($\rho = -0.35$, $p < 0.05$) (Fig. 8).

Foot placement was a significant predictor of post-transition foot readjustments during ladder descent ($\chi^2 = 15.37$; $p < 0.001$), where more posterior foot placement was associated with an increased occurrence of readjustments (Fig. 9). A 25% increase in foot placement in this model would result in an Odds Ratio of 0.01, indicating that a climber would have 99% reduced odds of repositioning their foot given this shift in foot placement. There were not enough post-transition foot readjustments in ascending trials to power a logistic regression.

## 4. Discussion

Our results indicated that the reversed fly configuration offered improvements in most of our metrics but performed comparably to or was outperformed by the traditional fly configuration in a few metrics. Ladder configuration influenced foot placement, with the reversed

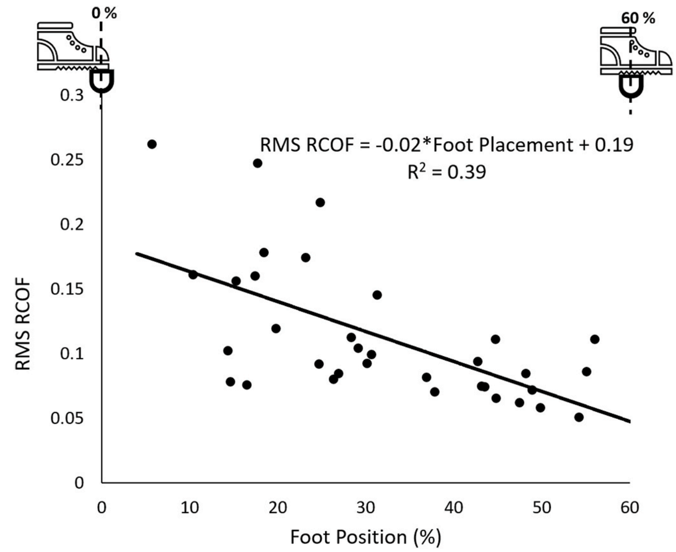


**Fig. 7.** RMS RCOF for the third phase of stance against foot position including the line of best fit where increased foot position indicates rung contact closer to the heel. Graphics at top of the figure show foot position at 0% (left) and at 60% (right).

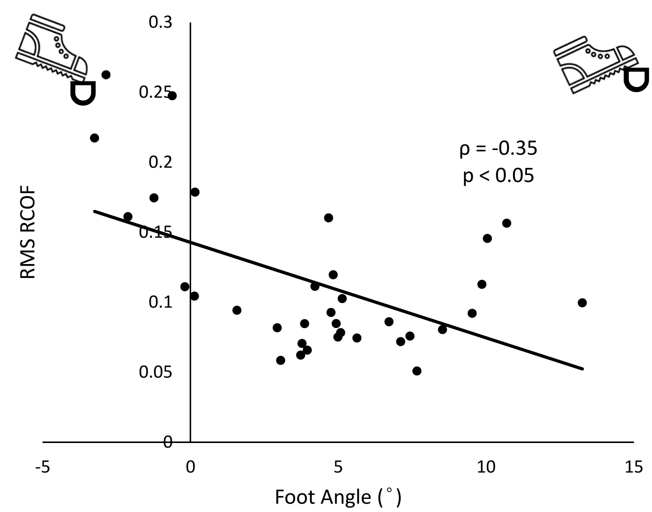


**Fig. 8.** Plot of RMS RCOF for the third phase of stance against foot angle where negative values indicate plantar flexion, positive values indicate dorsiflexion, and 0 indicates neutral stance. The graphics at the top of the figure show the foot in plantar flexion (left) and dorsiflexion (right).

configuration having farther posterior placements during ascending climbs and farther anterior placements when descending, compared to the traditional configuration. Ladder configuration did not influence the RCOF peaks in early to mid-stance for ladder descent. During the late stance phase, the reversed fly configuration resulted in lower RMS RCOF. Foot placement and foot angle partially explained the RCOF changes with rung contact closer to the toes and increased plantar flexion corresponding to increased RCOF. The reversed fly configuration also decreased adverse stepping events and increased user preference compared to the traditional configuration. Foot placements predicted the occurrence of foot readjustments after the descending transition, the most common adverse stepping event. The combined benefits of farther anterior descending foot placements, reduced frictional requirements, fewer adverse stepping events, and improved user preference provide some justification for pursuing future research and development work

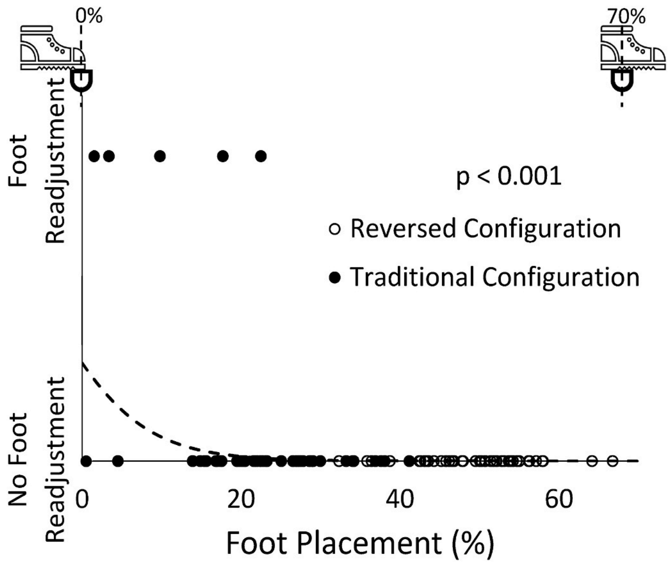


**Fig. 9.** Logistic regression of foot readjustments against foot placement, with higher values indicating farther anterior foot placement relative to the rung. Posterior foot placement values predicted a greater occurrence of a foot readjustment. Filled circles represent trials where the participant was descending the traditional ladder, empty circles represent trials where the participant was descending the reversed ladder, and the dashed line represents the logistic fit equation.

around the reversed ladder configuration.

The results are consistent with past literature investigating the impact of foot orientation on slip and misstep risk during ladder climbing. The results found plantar flexed foot angles to be associated with higher RCOF values, counter to our hypothesis and previous straight ladder work on ladder ascent (Martin et al., 2020). However, our foot angles agreed with prior work from Griffin et al. that found a positive correlation between increased foot plantar flexion and increased RCOF values when transitioning from a roof to ladder during ladder descent (Griffin et al., 2023). This work, along with this previous literature, indicates that the effect of foot angle on RCOF may be different for ascent and descent. Our significant relationship between anterior foot position relative to the rung and RCOF were consistent with the non-significant trend found by Martin et al. (2020). There were some modest differences between our results and their findings, that could be due to variations in task (ascent vs. descent) and the frictional requirement metrics (e.g. RCOF peak versus RMS RCOF). Prior work by Pliner et al. that examined slip outcome rather than RCOF produced findings consistent with this study (farther anterior foot placement relative to the rung associated with increased slip risk) (Pliner et al., 2014). This study also found that foot placement influenced foot readjustments with farther posterior shifts in foot placement being associated with increased risk of adverse events. This was consistent with prior research that identified the impact of foot placement on slip or missed step risk (Pliner, 2020; Pliner et al., 2014).

Similarly to foot orientation, the RCOF magnitudes are consistent with past literature. The magnitude of the RCOF peak values agreed with past work by Martin et al., which found an average RCOF value of 0.15 for climbing at a 75° angle (Martin et al., 2020). These magnitudes were consistent with our findings for peak types B and C during initial foot contact. The peak type A RCOF values (mean of 0.69) were larger than the results of Martin et al. magnitude values, likely due to a lower normal force cutoff criterion. Additionally, the difference in RCOF between configurations (0.04) during the 3rd phase of stance was found to be similar in magnitude to other factors found to have meaningful differences (Griffin et al., 2023; Martin et al., 2020). This difference of 0.04 is also four times the increase (0.01) that had been found to lead to 73% higher odds of slipping in level walking literature (Beschorner et al., 2016), indicating that this difference is meaningful.

The differences in foot placement between fly conditions during ladder climbing may be explained by incongruence between the environmental conditions and the motor control strategy. The execution of repetitive locomotor tasks (walking and climbing) contains variability (Hausdorff, 2007) that is influenced by sensorimotor function (Taylor et al., 2012) and cognitive factors (e.g. distraction and fatigue) (Behrens et al., 2017; Licence et al., 2015). Ongoing attentional processes can influence locomotor performance. For example, supervisory attention models influence motor performance and are typically separated into: 1) actions requiring low cognitive resources relying primarily on procedural memory, and 2) actions that require high levels of attention especially for novel situations (Baddeley, 1986; Norman and Shallice, 1986). Climbing most ladder steps, apart from the first and last rungs, are well-learned and repetitive, allowing users to rely upon their procedural memory. However, climbing an extension ladder introduces a transition step in the middle of this typical repetitive motion which may require users to proceed with either error correction or additional planning achieved through additional attentional resources. Transition errors in stair climbing occur, when there is an unexpected change in step height during gait that results in error corrections due to the disruption of the typical action sequence (van Dieën et al., 2007). Relevant to our study, continued stepping without an adjustment would be expected to result in foot/rung contact opposite the direction of the transition shift (i.e., a posterior rung shift at the transition would result in a more anterior foot placement). Consistent with this expectation, the foot placement was found to shift opposite to the rung shift for both configurations (Figs. 4 and 5). Thus, the influence of cognitive processes on climbing biomechanics may help explain differences in responses to ladder designs.

The results support future research and development work toward a reversed fly configuration because of observed effects on friction, foot placement, adverse stepping events, and preference. In each of these metrics, the reversed fly configuration had similar or preferable results compared to the traditional configuration except for foot placements during ascent. For the traditional ladder, the farther anterior foot placement during ascent might be advantageous for preventing slips or missteps. However, it was also accompanied with more frequent instances of kicking a rung. Thus, the net benefit of a traditional ladder during ascent is unclear. However, these metrics are only a subsection of the factors that must be investigated before any broad changes are made to extension ladder design. Within these metrics alone, additional work is needed to verify that a reversed fly is safe across various use conditions, such as work on the extension ladder or transitioning to/from a roof surface. Additionally, any changes would require additional human factors testing and mechanical testing.

One limitation of the study was the height restrictions in the laboratory which resulted in a transition starting at 0.9 m (3 rungs) off the ground, lower than typical extension ladders. The laboratory setting may have caused participants to climb differently than they would have in a typical outdoor setting, such as a worksite. Finally, the RCOF analyses only included descent trials and further work is needed to better understand the effect of different ladder fly configurations on the slip risk during extension ladder ascents.

## 5. Conclusion

This study found that a reversal of the traditional fly position offered potential improvements in multiple ladder safety metrics such as foot placement, frictional requirements, and adverse stepping events. The reversed configuration had farther anterior foot placements in descent, lower RMS RCOF values during late stance in descent, and fewer adverse stepping events than the traditional configuration. Although the reversed configuration did show improvements in most metrics, the traditional configuration did have farther anterior foot placements in ascent. These findings, along with increased user preference, support future research and development into the reversed fly ladder design as a potential product to prevent ladder fall injuries.

## CRediT authorship contribution statement

**Violet M. Williams:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sarah C. Griffin:** Writing – review & editing, Investigation, Data curation, Conceptualization. **Mark S. Redfern:** Writing – review & editing, Conceptualization. **Kurt E. Beschorner:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apergo.2024.104371.

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