



During roof-to ladder transitions, walk-through extensions modify required friction direction

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ABSTRACT

Severe and fatal falls involving ladders commonly occur during transitions across the ladder and another support surface. Slipping is a common initiating event in ladder falls. This study characterized the friction requirements and body kinematics of descending roof-to-ladder transitions with and without a walk-through extension. Healthy adults who regularly climb ladders ($n = 17$) completed descending roof-to-ladder transitions, while foot-rung kinetics and body kinematics were recorded. The peak required coefficient of friction (RCOF) with respect to the plane of the shoe sole was calculated. The RCOF and body angle were calculated using their resultant values and projections in the frontal and sagittal planes. Foot angle was calculated in the sagittal plane. Repeated-measures ANOVA determined that compared to a walk-through ladder, a traditional ladder was associated with a higher RCOF in the medial-lateral (ML) direction ($F_{1,16} = 190.07$, $p < 0.001$) and a lower RCOF in the anterior-posterior (AP) direction ($F_{1,16} = 11.02$, $p = 0.004$), but had no significant relationship with the resultant RCOF ($F_{1,16} = 0.098$, $p = 0.76$). Spearman's rho tests performed across all testing configurations identified significant associations between foot angle and overall RCOF ($r_s = -0.724$, $p < 0.001$), foot angle and AP RCOF ($r_s = -0.871$, $p < 0.001$), and frontal plane body angle and ML RCOF ($r_s = 0.782$, $p < 0.001$). Clustering in the data suggests that ladder attachments reduced frontal plane kinematics, which altered the direction of RCOF by reducing the medial-lateral component. These results have implications for designing rungs with good friction in multiple directions and the potential for body position monitoring in ladder tasks.

1. Introduction

Falls from ladders pose a threat to human safety, both at and away from work (Björnstig and Johnsson, 1992, Partridge et al., 1998). In 2019, 171 work-related fatalities and 22,330 non-fatal incidents were reported with ladders as the primary source (U.S. Bureau of Labor Statistics, 2023). Falls may occur during standing, balancing, dynamic climbing, or transitioning to or from the ladder. Slips or a loss of balance are one of the top reasons for falling from a ladder (Cohen and Lin 1991, Shepherd et al., 2006, Smith et al., 2006), but there is a paucity of research in the mechanistic causes of ladder slip events.

About 20% of falls involving ladders are during transitioning tasks (Shepherd et al., 2006) indicating that transitions, such as from a roof to a ladder or vice-versa, are particularly dangerous for workers. In a roof-to-ladder transition using a traditional extension ladder, the ladder should extend 0.9 m above the roof surface (U.S. Occupational Safety and Health Administration, 2014). Typically, the user stands next to the

top of the ladder facing the center of the roof. Then they step back, around the top of the ladder, and onto a rung. Ladder transition events increase the risk of falls in two main ways: 1) the applied forces may cause the ladder to tip or slide out; or 2) the individual may slip or misstep on the rung to which they are stepping (Cohen and Lin, 1991). As a potential solution to the dangers associated with roof-to-ladder transitions, a class of attachable accessories has been developed that allow the user to move between the two attachments instead of around the ladder. The different path of motion associated with these attachments is believed to mechanistically increase the safety (Ellis, 2017). Previously, Simeonov et al. (2017) investigated ascending and descending transitions with traditional and walk-through ladders. The authors' primary goal was to determine the likelihood of the ladder tipping or sliding out during the motion but found no meaningful difference in the required friction between the ladder feet and the ground. To our knowledge, no studies have yet addressed the impact of the descending transition task on the risk of the user's shoe or boot slipping

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relative to the ladder rung.

Another factor that may be important in roof-to-ladder transitions is the pitch of the roof. Roof surfaces can be flat, common in commercial buildings, or pitched, common in residential buildings. A transition task is expected to be more difficult from a pitched roof because of the impact of incline angle on stability and friction requirements (McVay and Redfern, 1994, Hanson et al., 1999, Dutt-Mazumder et al., 2016, Simeonov et al., 2017, Breloff et al., 2019). It has yet to be studied if a pitched roof surface increases the chances of foot slip during transition.

The required coefficient of friction (RCOF) between the worker's shoe and ladder rung may provide insight into slip risk during the ladder transition. RCOF is a task- and individual-specific metric that quantifies the amount of friction necessary for an individual to complete a task without slipping. It has been found to be predictive of slips in level walking (Beschorner et al., 2016). RCOF is determined by analyzing the ratio of shear to normal forces during foot contact and extracting a peak which represents the amount of friction needed to complete a task. One study quantified the RCOF during steady state ladder ascent (Martin et al., 2020), but this metric has yet to be determined in ladder transition tasks or for descent. The RCOF and slip risk of straight ladder climbing have been correlated with foot and body angles during ascent (Pliner et al., 2014, Martin et al., 2020). The relationship between the center of mass and base of support (body position) has also been correlated to the direction of the required friction during walking (Yamaguchi et al., 2018). Foot and body positioning may be a relevant mechanism for explaining RCOF variation during roof-to-ladder transitions.

The purpose of this study is to determine the relationship between extension ladder top (traditional vs. walk-through) and roof incline angle on the RCOF during descending roof-to-ladder transitioning events. It is hypothesized that RCOF will be higher for a traditional ladder compared to a walk-through ladder and a pitched roof compared to a flat roof. The secondary purpose is to determine the relationship between an individual's kinematics (i.e., foot and body angles) and RCOF during roof-to-ladder transitions.

2. Methods

Biomechanical parameters related to slip risk were measured for a combination of two ladder types (walk-through and traditional) and two roof surfaces (flat and pitched). Written informed consent was obtained at the start of the study and procedures were approved by the University of Pittsburgh Institutional Review Board. This research was performed in accordance with the Declaration of Helsinki of 1975.

2.1. Participants

Seventeen healthy participants (9 M, 8 F, mean \pm standard deviation: age = 33.9 ± 15.3 years, weight = 76.6 ± 15.5 kg, height = 1.73 ± 0.087 m, BMI = 26.1 ± 3.3 kg/m²) from a pool of twenty individuals were analyzed in this study. To be recruited, individuals had to meet a set of self-reported inclusion criteria: no recent musculoskeletal injury, no balance disorders, and no fear of heights. They had to have a weight under 136 kg to comply with the safety equipment and a height under 1.96 m due to lab height restrictions. Finally, participants had to report that they climb ladders at least four times per year. Participants from the recruited pool were excluded if they showed atypical climbing behavior such as adjusting the foot after it contacts the rung ($n = 2$ participants) or due to technical problems which resulted in poor data quality ($n = 1$ participant).

2.2. Experimental protocol

Participants encountered two ladder conditions and two roof conditions (Fig. 1). Scaffolding at the height of the fourth ladder rung represented the *flat roof* conditions. A 22.4° ramp was rigidly attached for the *pitched roof* conditions. This angle is within the range of typical



Fig. 1. Images of the testing configurations.

roof pitches ($18\text{--}34^\circ$) (Simeonov et al., 2003). The *traditional ladder* was a commercially available single-section ladder (length = 2.43 m). The *walk-through ladder* attachments (AES Raptor Grabsafe) were fixed to a section of the same type of ladder (length = 1.52 m), resulting in the same total length as the traditional ladder. While other similar attachment designs exist with varying handhold designs, they all are expected to alter the kinematic path similarly since they allow the user to step between the attachments instead of around the ladder. The third rung (called the transition rung herein) was attached to a force plate (AMTI Inc., Watertown, MA, USA) which collected three dimensional forces. An air gap between the instrumented rung and the rest of the ladder ensured forces were isolated. Ladders were set at $75 \pm 1^\circ$ (Occupational Safety and Health Administration, 1990) and secured to the scaffolding.

Participants wore tight fitting clothes, a safety helmet, harness, and their own shoes or boots that they would typically use for climbing a ladder. Footwear was not controlled to increase the generalizability of this work. Participants wore 79 reflective markers which were tracked by 12 motion capture cameras (Vicon T40s cameras, Vicon Motion Systems Ltd., Centennial, CO, USA). Participants performed three ascending and three descending transition trials for each roof-ladder combination. This analysis only includes descending trials where they began standing on the roof surface. Participants were instructed to step to the transition rung and descend the ladder at a comfortable but urgent pace, like how they would move while completing a task under time pressure at work or home. Participants completed at least one practice trial in each configuration and were given seated rests frequently.

2.3. Data analysis

Marker data was filtered with a 7th-order lowpass Butterworth filter with a cutoff frequency of 10 Hz and kinetic data was filtered with a 9th-order lowpass Butterworth filter with a cutoff frequency of 35 Hz. Markers placed on the shoe defined a coordinate system for the plane of the bottom of the shoe which forms the contact plane in the shoe-rung interaction (Martin et al., 2020) (Fig. 2). Using the neutral foot

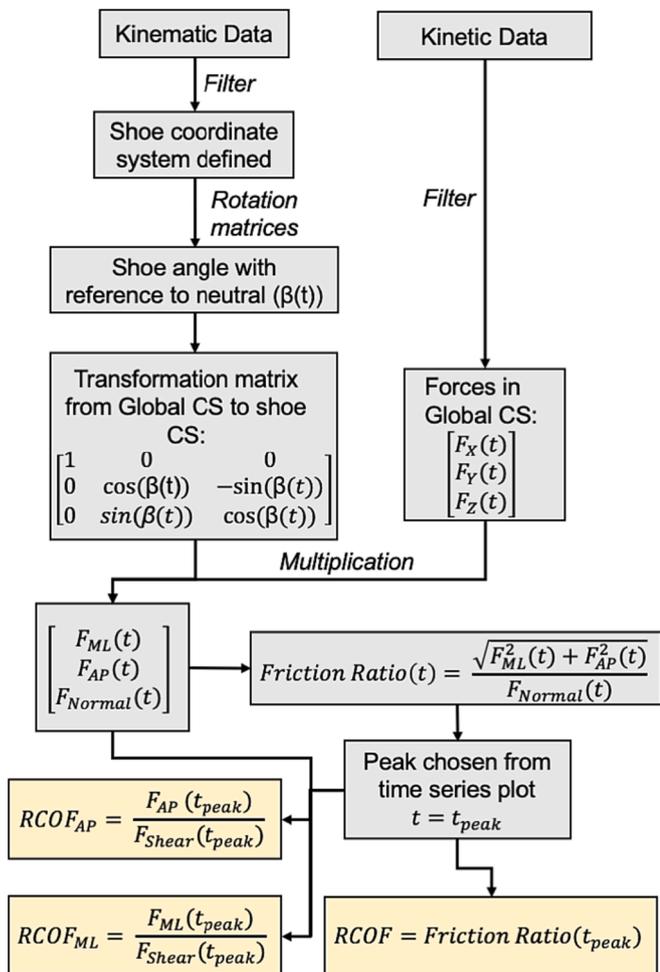


Fig. 2. The data processing pathway. Variables are defined in the figure or the text and t represents time.

position during standing as the reference orientation (0°), the shoe angle about the medial/lateral axis was calculated over time during the dynamic trials (Fig. 3). A transformation matrix rotated the reaction forces

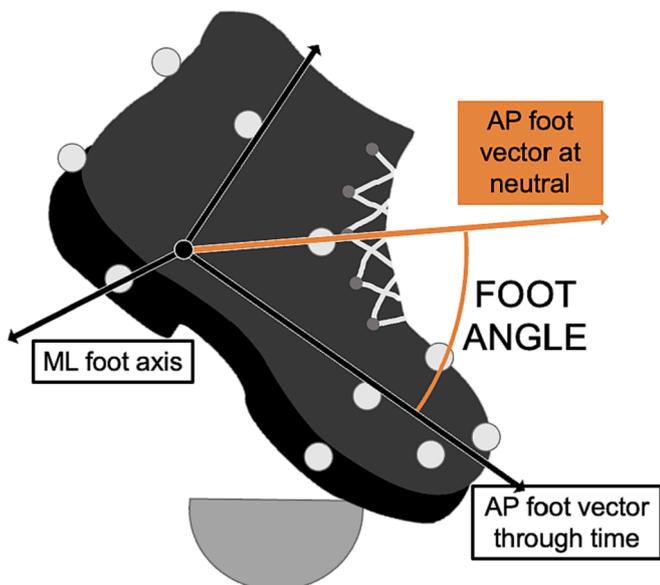


Fig. 3. Diagram of the foot angle.

from the force plate to the orientation of the shoe (Martin et al., 2020). The ratio of the magnitude of the resultant shear force to the magnitude of the normal force was calculated over time. Time-series plots were generated and visually inspected for trends to develop a protocol for selecting peaks potentially relevant to slip risk (Fig. 4). Two peaks were identified as potential RCOF locations due to their presence across nearly all participants and configurations. Further analysis determined that the second peak is likely more important in the occurrence of slips due to higher shear forces. Therefore, this analysis will discuss peak 2 (called the RCOF peak herein). The time corresponding to the RCOF peak was used to extract the data points for each of the metrics of interest.

The outcome variables were RCOF, ML RCOF (RCOF projection in the frontal plane), AP RCOF (RCOF projection in the sagittal plane), foot angle, body angle, ML body angle (body angle projected in the frontal plane i.e., medial/lateral lean), and AP body angle (body angle projected in the sagittal plane i.e., anterior/posterior lean). All metrics were calculated at the time of the RCOF peak. The body angle was defined by a vector from the toe center to the trunk center of mass (Pliner et al., 2014, Martin et al., 2020). The overall body angle was the angle between the body vector and vertical. AP and ML body angle were decomposed into the sagittal and frontal planes respectively (Yamaguchi et al., 2018) (Fig. 5).

2.4. Statistical analysis

Three repeated measures ANOVA tests were conducted with the RCOF, ML RCOF, and AP RCOF as dependent variables and roof condition, ladder condition, and their interaction as independent variables. Due to a lack of normality in residuals of bivariate regression analyses, a series of five Spearman's rho tests were used to evaluate the impact of foot and body angle on the RCOF. The predictor was the foot or body angle metric and the corresponding RCOF value was the dependent

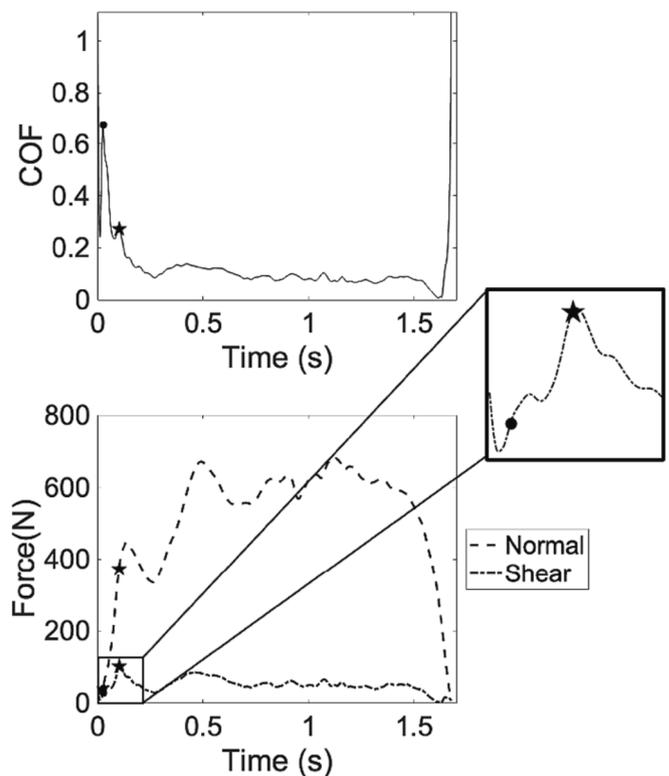


Fig. 4. Plots of the coefficient of friction and the normal and shear forces during the entirety of foot contact on the transition rung for one representative trial. The circle marks the location of peak 1 and the star denotes peak 2.

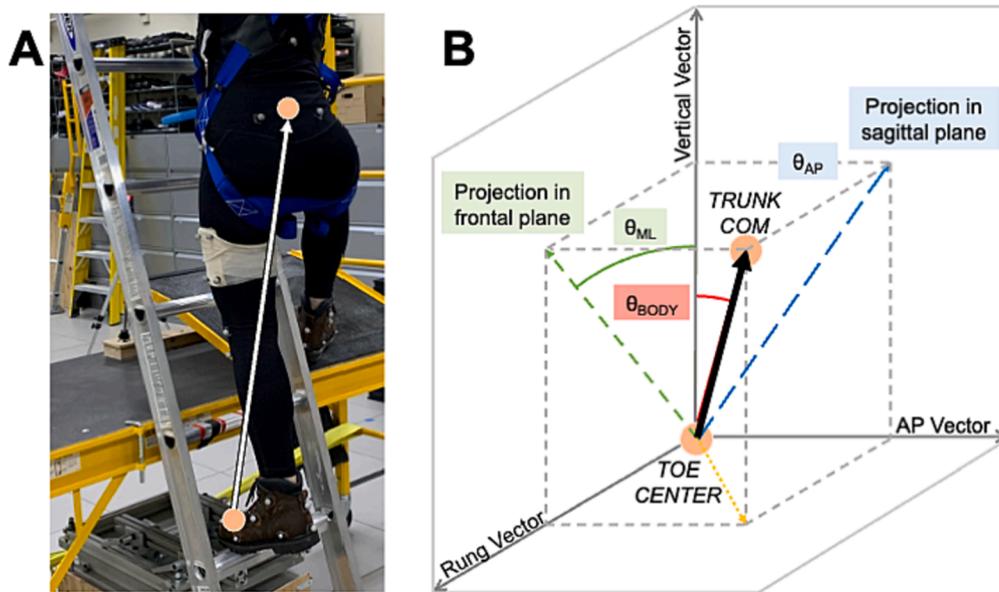


Fig. 5. A) An individual stepping from the roof to the ladder with the trunk center of mass (COM) and toe center labeled. B) Visual representation of the body angle. This method of resolving angles into planes is similar to that presented in Yamaguchi, Okamoto et al. (2018).

variable (i.e., ML body angle only regressed against ML RCOF and not AP RCOF or RCOF). Tests were evaluated with a Type I error level of 0.05.

3. Results

3.1. Description of the kinetics through time

Time-series plots of the friction ratio were reviewed to identify peaks

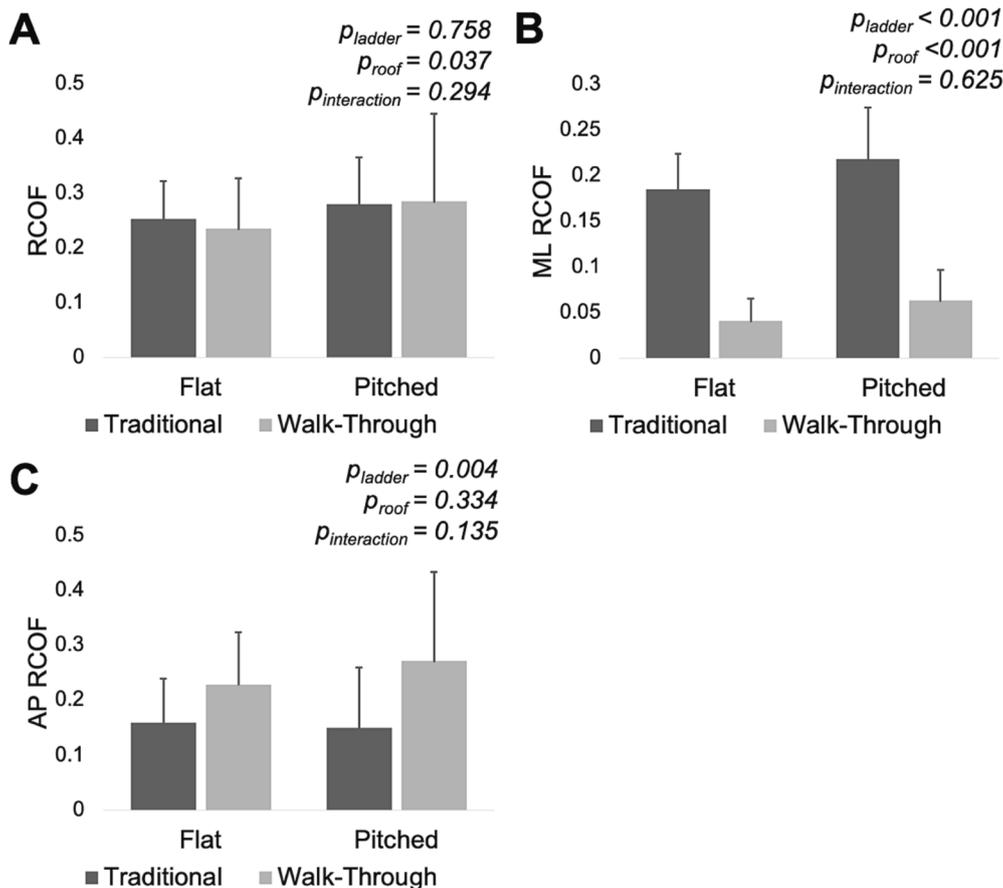


Fig. 6. Plot of the A) overall RCOF, B) Medial/Lateral RCOF, and C) Anterior/Posterior RCOF. Bars represent the different test conditions and error bars represent standard deviations. P-values for all effects are listed on the plots.

relevant to slip risk (Fig. 4). Two peaks were observed in the early stance phase. Peak 1 was located an average of 25.8 ms after the initial foot contact and had an average value of 0.638 (SD = 0.203) across participants and conditions. This peak was associated with low normal forces (mean = 85.2 N, SD = 58.1 N) and shear forces (mean = 47.2 N, SD = 28.3 N). Peak 2 was located an average of 94.6 ms following foot contact and had an average value of 0.262 (SD = 0.123) across participants and conditions. It was associated with higher forces (normal: mean = 324.2 N, SD = 212.5 N; shear: mean = 75.1 N, SD = 53.2 N). Of the 204 trials collected, peak 1 was present in 168 trials and peak 2 in 148 trials. The research team concluded that, despite the lower RCOF values, peak 2 is more relevant to slips because it corresponds to greater forces and likely leads to larger foot acceleration values.

3.2. Effect of testing condition on frictional requirements

Ladder type affected the directionality of required friction but not the overall magnitude. There was no significant effect of ladder type on the RCOF ($F_{1,16} = 0.098$, $p = 0.76$), nor was there a meaningful trend (Fig. 6). Roof condition had a significant effect on the RCOF ($F_{1,16} = 5.16$, $p = 0.037$) where the pitched roof corresponded to a higher RCOF than the flat roof. The interaction of these factors was not significant ($F_{1,15} = 1.18$, $p = 0.29$). The medial/lateral friction component showed a significant effect for both the ladder ($F_{1,16} = 190.07$, $p < 0.001$) and roof conditions ($F_{1,15} = 16.92$, $p < 0.001$), but not for the interaction of these factors ($F_{1,17} = 0.25$, $p = 0.625$). Average values indicate that a traditional ladder has a higher ML RCOF than a walk-through ladder and

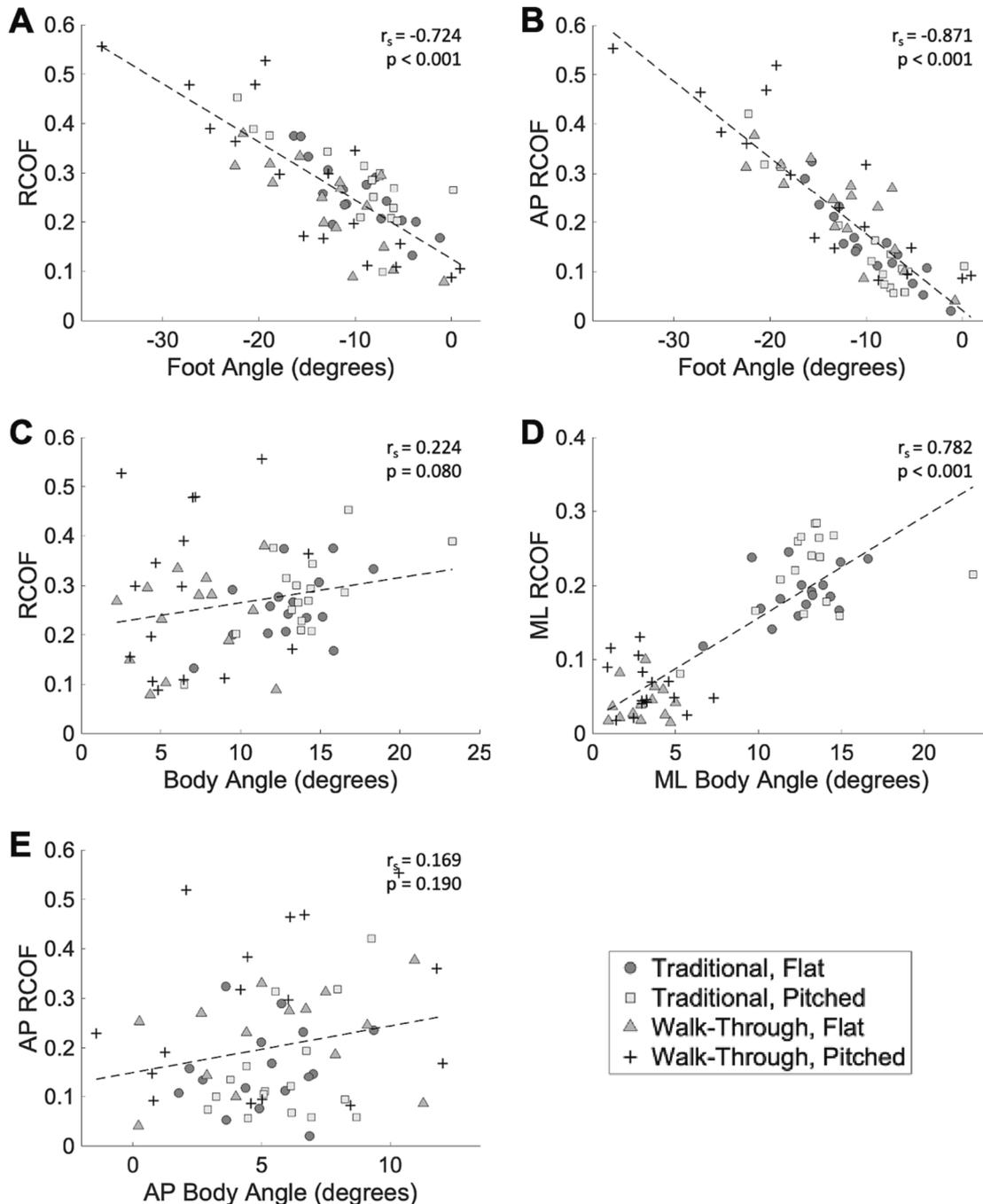


Fig. 7. A) plot of the RCOF peak versus the foot angle, B) plot of the AP RCOF versus the foot angle, C) plot of the RCOF peak versus the overall body angle, D) plot of the ML RCOF versus the ML body angle, and E) plot of the AP RCOF versus the AP body angle.

a pitched roof has a higher ML RCOF than a flat roof. A pitched roof with a traditional ladder top had an average ML RCOF more than 5 times larger than a flat roof and a walk-through ladder. Analyses on AP RCOF found a significant effect of the ladder type ($F_{1,16} = 11.02$, $p = 0.004$), but not the roof condition ($F_{1,16} = 0.99$, $p = 0.33$) or the interaction ($F_{1,15} = 2.49$, $p = 0.14$). A walk-through ladder had a higher AP RCOF than the traditional ladder.

3.3. Analysis of kinematics

Bivariate analysis of friction requirements and corresponding kinematics indicated a relationship between the overall RCOF and foot angle and the RCOF and body angle in the frontal plane (Fig. 7). A significant, strong negative relationship was found between foot angle and RCOF ($r_s = -0.724$, $p < 0.001$). As the foot approached neutral (zero degrees), the RCOF decreased. Isolating the RCOF in the AP direction strengthened the relationship with foot angle ($r_s = -0.871$, $p < 0.001$). A weak and insignificant positive relationship was found between the overall body angle and RCOF ($r_s = 0.224$, $p = 0.080$) with a higher RCOF associated with a greater angle from vertical. A strong relationship was found between the ML body angle and the ML RCOF ($r_s = 0.782$, $p < 0.001$). A higher ML body angle corresponds with the individual leaning away from vertical. As can be seen in Fig. 7C, clustering across ladder types (indicated as different marker types) was observed with the walk-through ladder associated with lower ML RCOF and ML body angles than the traditional ladder. Thus, body angle might explain the ML RCOF effects between these two ladders. A weak and insignificant positive relationship was discovered between the AP body angle and AP RCOF ($r_s = 0.169$, $p = 0.190$).

4. Discussion

This study found that walk-through attachments alter the directionality of the RCOF for roof-to-ladder transitions, but not its overall magnitude. Roof pitch increased the RCOF compared to a flat roof, primarily due to an increase in the ML RCOF. It is possible that the impact of the roof pitch would scale with higher pitch angle. Body mechanics, including foot and body orientation, partially explained the directionality of RCOF during transition events. This increased understanding of frictional requirements during roof-to-ladder transitions may provide justification for ladder design changes and recommendations for safer transitioning.

4.1. Kinetics of ladder transitions

RCOF values reported in this study deviated from previous research, likely due to differences in task or analysis methods. RCOF values in this study are higher than those observed for steady state ladder ascent (Martin et al., 2020); previously, an average RCOF of 0.149 at a ladder angle of 75° was calculated, which is just over half the magnitude in this study (0.263). The increased complexity of a descending roof-to-ladder transition compared to steady state ascent could explain this finding. One other study which assessed ladder climbing (Bloswick and Chaffin, 1990) found a horizontal to vertical force ratio of 0.4, which is higher than the value found here. However, it is not clear how the authors picked the RCOF peak and they did not use a coordinate system rotated to the friction plane of the shoe for its calculation. Therefore, methodological differences likely explain this variation in friction requirements.

The direction of resultant forces indicate that a person's foot is more likely to slip forwards or laterally than backwards in a roof-to-ladder transition. Previously Bloswick and Chaffin (1990) hypothesized that frictional requirements of ladder climbing would cause a forward slip. However, perturbation studies which included a slip from a ladder rung resulted in the foot sliding backwards and off the rung (Pliner et al., 2014, Schnorenberg et al., 2015). It is possible that the different motion profile associated with transition compared to steady state climbing

reverses the slip direction. During a forward slip, there may be an increased risk of the body impacting the ladder, causing the ladder itself to fall. A forward slip of a single leg could lead to the legs straddling and contacting the rung to arrest the fall. High ML RCOF values for the traditional ladder also indicate a possibility for a lateral slip where the foot travels along the length of the rung. The biomechanics of lateral slips have not been fully described and the ability for an individual to recover is unknown. However, a severe lateral slip could cause the foot to contact one of the rails, resulting in a lateral ladder tip, which is commonly described in literature (Cohen and Lin, 1991, Shepherd et al., 2006, Simeonov et al., 2017).

To our knowledge, this is the first ladder study which includes the ML RCOF. High RCOF values were found in the ML direction for the traditional ladder, which highlights a potentially important need for ladder rung designs to provide ML-oriented friction. However, ladder rungs are frequently designed with directional ridges oriented in the long axis of the rung (Fig. 8). Presumably, ridges help increase traction on the rung in the anterior/posterior direction because they are a barrier that the shoe needs to move or deform around during sliding. Longitudinal topographical features increase friction in one direction but decrease friction in the perpendicular direction (Menezes et al., 2006, Darden and Schwartz, 2013). Thus, these features may decrease the available friction for sliding along the ridges (i.e., the medial/lateral direction). Because a traditional transition task may require a high amount of ML friction, these rungs may have risk for ML slips even if they are safe in the AP direction.

4.2. Relationship between kinetics and kinematics

This study found a significant relationship between foot angle and RCOF where the foot tended to be in plantarflexion at the time of the RCOF peak. Previous literature has also found this relationship, but in



Fig. 8. An image of the rung cross-section. Note the ridges traveling along the length of the rung.

steady state ascent the foot tended to be in dorsiflexion (Pliner et al., 2017, Martin et al., 2020). The direction of these motions may explain the foot orientation. While descending, the leg is lowered towards the next rung and initial contact occurs with the toe pointed towards the ground. The opposite motion occurs in ascent. The impact of the foot angle on the RCOF indicates that it may be advantageous for individuals to contact the ladder rung with a flatter foot during roof-to-ladder transitions.

ML body angle correlated well with ML RCOF, but no correlations were observed between overall body angle and RCOF or AP body angle and AP RCOF. The significant correlation between the ML body angle and ML RCOF was consistent with Yamaguchi et al. (2018) who found a similar result during walking tasks. Although there was no significant correlation in the AP and overall directions, the trend was in the same direction as previous work that found individuals who slipped leaned further from the ladder while climbing (Pliner et al., 2014) and the RCOF was positively correlated with body angle in steady state ascent (Martin et al., 2020).

There are a few limitations with the study. Due to height restrictions, the simulated roof surface was only approximately 1.25 m (4 rungs) above the ground. The lower height could have changed the participant's perceived risk (Simeonov et al., 2003), resulting in different behavior. Additionally, the ladder's reduced height decreases the moment arm for lateral forces and reduces the risk of lateral tipping. Only one type of walk-through attachment was used. Although we expect it to be representative of other similar attachments, differences in models may impact the results. Specifically, the shape of handholds is known to affect grasping forces (Young et al., 2009), which may have modest impacts on the results. Furthermore, the lab-based setting instead of a worksite could have caused people to act differently than they would in a true roof transitioning event. This study only considered the descending transition task and further work is needed to understand the ascending task. Finally, more perturbation studies which relate RCOF to slip risk are needed to increase our real-world understanding of this metric and these findings.

5. Conclusions and practical applications

This study demonstrates the relationship between ladder attachments, roof pitch, and body positioning with the frictional requirements of roof-to-ladder transitions. Although walk-through attachments did not significantly alter the overall RCOF of roof-to-ladder transition, they did alter the directionality of the RCOF and lowered the ML component. Due to the relationships between body angle (particularly in the ML direction) or foot orientation and the RCOF, it is recommended that individuals attempt to perform transitions with their feet less plantar-flexed and their center of mass as close to the transition foot as possible. This could minimize the required friction and subsequent slip risk. Use of walk-through attachments could help lower the risk of a lateral slip for rungs that do not have sufficient ML friction.

CRedit authorship contribution statement

Sarah C. Griffin: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing - Original draft. **Violet Williams:** Formal analysis, Investigation, Methodology, Software, Validation, Writing - review & editing. **Natasa Vidic:** Formal analysis, Methodology, Writing - review & editing. **Kurt E. Beschorner:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Writing - review & editing.

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.

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