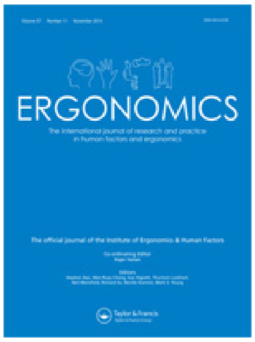

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Effects of foot placement, hand positioning, age and climbing biodynamics on ladder slip outcomes

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Ladder falls frequently cause severe injuries; yet the factors that influence ladder slips/falls are not well understood. This study aimed to quantify (1) the effects of restricted foot placement, hand positioning, climbing direction and age on slip outcomes, and (2) differences in climbing styles leading to slips versus styles leading to non-slips. Thirty-two occupational ladder users from three age groups (18–24, 25–44 and 45–64 years) were unexpectedly slipped climbing a vertical ladder, while being assigned to different foot placement conditions (unrestricted vs. restricted toe clearance) and different hand positions (rails vs. rungs). Constraining foot placement increased the climber's likelihood of slipping ($p < 0.01$), while younger and older participants slipped more than the middle-aged group ($p < 0.01$). Longer double stance time, dissimilar and more variable foot and body positioning were found in styles leading to a slip. Maintaining sufficient toe clearance and targeting ladder safety training to younger and older workers may reduce ladder falls.

Practitioner Summary: Ladder falls frequently cause severe occupational fall injuries. This study aims to identify safer ladder climbing techniques and individuals at risk of falling. The results suggest that ladders with unrestricted toe clearance and ladder climbing training programmes, particularly for younger and older workers, may reduce ladder slipping risk.

Keywords: ladder falls; climbing biomechanics; aging; slips, trips and falls

1. Introduction

Ladder falls are a frequent cause of occupational injuries. In 2011, falls to lower levels caused 12% of fatal work injuries (BLS 2012) and ladder falls were the second leading cause in falls to lower levels (Webster 2000). More than 50% of fall injuries experienced from mining equipment, which often require use of a ladder to ingress/egress, result in a fracture or sprain (Moore, Porter, and Dempsey 2009). The third largest causality insurance provider in the USA reported that workers' compensation costs for falls to lower levels were $5.12 billion in 2010 (Liberty Mutual Research Institute for Safety 2012). In a study surveying ladder fall fractures in 2000, 48% of these injuries resulted in $5000 or more in medical cost with 56% disabling the climber for 28 or more days (Smith et al. 2006). The high frequency, cost and amount of workdays lost due to ladder falls indicates a serious need to investigate how ladder design and climbing techniques influence falling risk.

Ladder falls can be broadly categorised into falls from ladders and falls with ladders. Falls from ladders typically occur due to decoupling of the hand and/or foot with the ladder (Hsiao et al. 2008; Partridge, Virk, and Antosia 1998; Shepherd, Kahler, and Cross 2006; Smith et al. 2006). Falls with ladders typically occur due to the ladder tipping over, falling away from a wall or collapsing due to excessive reaching or improper ladder placement (Partridge, Virk, and Antosia 1998; Smith et al. 2006). Previous research on ladder falling has primarily focused on ladder set-up and the risk of the ladder tipping away from the wall or the feet slipping against the ground in an effort to prevent falls with ladders (Chang, Chang, and Matz 2005). Few studies have investigated the beginnings to falls *from* ladders (Hsiao et al. 2008). This gap in the literature is surprising given that falls from ladders are the most common reason for ladder-related fractures (Smith et al. 2006). The most common initiating event for a fall from a ladder is due to a person's overbalance, slip or misstep (Shepherd, Kahler, and Cross 2006). Slipping occurs when the friction between the shoe and rung is inadequate to support climbing (Chang, Chang, and Matz 2005; Shepherd, Kahler, and Cross 2006); however, little is known about what other factors influence slipping risk.

The feet are the primary load-bearing interface during ladder climbing, while the hands are largely responsible for balancing the body during climbing and for recovery. Foot forces during climbing have been measured to be between 55% (Bloswick and Chaffin 1990) and 96% (Armstrong et al. 2009) of a climber's body weight. Bloswick and Chaffin suggest that low friction between the rungs and the feet may cause forward slipping of the foot based on analysis of horizontal and vertical forces. However, this conclusion was based on just the kinetics of climbing and did not simulate slipping. In order to

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maintain a solid footing surface during ladder climbing, the US Mining Safety and Health Administration (MSHA) requires that ladders be placed at least 76 mm away from other surfaces (United States Mining Safety Health Administration 1985), while the Occupational Safety and Health Administration (OSHA) requires a 180 mm clearance. Exceptions to the OSHA rule include ladders in elevator pits and certain ladders in marine terminals, which require 100–110 mm of clearance (United States Occupational Safety Health Administration 2003). These conflicting toe clearance rules suggest that an understanding on the effects of restricted toe clearance on slip risk is needed to assess the appropriateness of the different guidelines. When using a ladder, climbers must choose between grasping the vertical rails of the ladder or the rungs of the ladder. A slip or misstep can manifest into a fall event if the hand decouples from the ladder after the perturbation. Previous research has suggested that grasping the rungs may provide a better grip than grasping the rails (Armstrong et al. 2009; Barnett and Poczynck 2000; Young et al. 2009). Yet the effects of different hand grasping strategies on the risk of a slip have not been thoroughly examined. Determining if hand positioning affects slip risk is necessary to determine proper ladder climbing training. Lastly, previous evidence has suggested that a higher injury rate occurs while workers are egressing than while ingressing of mining equipment (Moore, Porter, and Dempsey 2009), suggesting that workers might be at greater risk of slipping during ladder descent than ascent. Yet, no controlled study has been performed to consider the effect of ascent versus descent on slip risk. This study aims to identify the effects of foot positioning, hand positioning and ascent versus descent on slip outcomes in order to better inform safer climbing.

Age may be another significant factor in ladder slip outcomes since slip and fall incidents increase with age. Non-fatal lower level falls show an uneven trend among working adults. The incidence rates of non-fatal lower level falls per 10,000 full-time workers initially decreases with age from 4.9 in adults aged 20–24 to 4.2 for adults aged 25–34, and then increases to more than 6 for adults older than 45 years (BLS 2013). Over the years, many studies investigated the possible reasons for aging as a factor in level walking falls. In view of the evidence that postural coordination differs in some fundamental ways among younger and older adults (Strang et al. 2013), it can be argued that the underlying mechanisms of falling and recovery would also differ with age. Age-related level walking falls were largely linked to various health-related issues, including diminished psychological and physiological functions (Blake et al. 1988; Barrett, Mills, and Begg 2010; Gehlsen and Whaley 1990; Lord 2007; Terroso et al. 2014). Maki et al. (2008) summarised several methodologies aimed at reducing risk of falling related to aging. Among various interventions described in the study, balance-enhancing footwear and handrails were identified to be crucial for the prevention of falls. In spite of the lack of fundamental studies specific to ladder falls, it can still be argued that the relationship between falls and age found for level walking can hold for ladder falls. If so, identifying the possible underling reasons for age-specific ladder falls may be important.

Furthermore, the effects of other factors like climbing forces, climbing speed, body positioning and foot positioning on slipping risk are relatively unknown. Previous studies that have initiated an unexpected slip during level walking have found that gait characteristics such as cadence, step length and ankle dorsiflexion influence slip risk (Marigold, Bethune, and Patla 2003; Moyer et al. 2006). Simulating ladder slips may reveal that similar critical variables influence slip risk on ladders, which may be useful to reducing ladder falls.

The first purpose of this study is to quantify the effects of restricted toe clearance, hand positioning, climbing direction and age on slip outcomes. The second purpose of this study is to quantify the differences in climbing biodynamics between participants who slipped versus participants who did not slip. In our study we developed the following hypotheses.

Hypothesis 1.1: Restricted toe clearance will increase the probability of slip.

Hypothesis 1.2: Hand positioning will not affect slip outcome.

Hypothesis 1.3: Slip rate will be higher with descending than with ascending climbs.

Hypothesis 2: Age will affect an individual's slip risk.

Hypothesis 3: Ladder climbing biodynamics such as foot forces, climbing speed, body positioning and foot positioning will be different between participants who slipped versus those who did not slip.

Table 1. Subject distribution amongst age groups with the mean ± standard deviation of age and body mass for each age group.

	Age group (yr)		
	18–24	25–44	45–64
Number of subjects (female)	11 (5)	12 (3)	9 (2)
Age (yr)	19.5 ± 2.0	39.4 ± 4.5	53.3 ± 5.6
Body mass (kg)	76.8 ± 17.0	83.9 ± 9.8	87.8 ± 14.9
Height (m)	1.7 ± 0.1	1.8 ± 0.1	1.7 ± 0.1

2. Materials and methods

2.1. Subjects

In this study, 32 (10 female) experienced ladder climbers volunteered to participate. Participants were recruited from demographics exposed to frequent ladder usage, such as firefighters, roofers, painters, construction works and divers. To qualify, participants needed to respond yes to a question that asked if they 'regularly used ladders'. The participants were separated into three age groups: 18–24 years (19.5 ± 2.0 yr, 76.8 ± 17.0 kg, 1.7 ± 0.1 m), 25–44 yr(39.4 ± 4.5 yr, 83.9 ± 9.8 kg, 1.8 ± 0.1 m) and 45–64 yr (53.3 ± 5.6 yr, 87.8 ± 14.9 kg, 1.7 ± 0.1 m) (Table 1). Body mass increased as subjects' age increased ($p < 0.01$). BLS (2013) reports incident rates for workers who fall into the following age categories: 16–19 years, 20–24 years, 25–34 years, 35–44 years, 45–54 years and 55–64 years. Therefore, each of the age ranges used in this study approximately corresponds to two age groups spanning 18 to 64 years. The protocol was approved by the University of Wisconsin-Milwaukee Institutional Review Board. Participants underwent phone screening to confirm eligibility. Exclusion criteria included musculoskeletal and neurological disorders, pregnancy and balance disorders. Written informed consent was obtained prior to testing.

2.2. Experimental approach

Participant's body mass, height and foot length were measured. Foot length was the distance from the most anterior point of the first toe to the posterior edge of the calcaneus. All participants were equipped with standardised attire, footwear and a safety harness. The footwear was a standard work shoe with a rubber sole and a raised heel. A total of 46 reflective markers were placed on anatomical landmarks of the participant and were tracked by 13 motion capture cameras at a frequency of 100 Hz (Motion Analysis Raptor Corp., Santa Rosa, CA). Five reflective markers were placed on the outside of the rails between the fifth and sixth rungs of a vertical 12-foot industrial-use ladder that was secured in the middle of the motion capture volume (Figure 1). The markers placed on the ladder allowed for determination of how the person was moving relative to the ladder. The rung and rail spacing on the ladder was within OSHA standards, spaced 279.4 and 463.6 mm

Figure 1. Ladder climbing set-up. The ellipse encircles the slip rung.

apart, respectively (United States Occupational Safety Health Administration 2003). All rungs, except for the fourth rung, were equipped with strain gauges. The fourth rung (slip rung) on the ladder was replaced with a rod and lockable bearings. The bearings were locked for non-slip trials and were unlocked for slip trials so that the rung could spin freely. The spinning, low friction rung was used to induce slips during the perturbation trials. The bearings were hid from participants' view with wood covers. At the bottom of the ladder was an impact mat and the participant had a spotter and a belayer throughout the ladder climbing trials to ensure their safety.

Participants were randomly assigned to two out of four different controlled climbing styles. Controlled climbing styles included two hand positions (rungs or rails) and two foot placement conditions (unrestricted or restricted toe clearance) (Figure 2). During trials where participants were assigned to restricted toe clearance climbing, a board was placed at a distance of 25% of the participant's foot length anterior to the ladder. This distance approximates the minimum requirements of MSHA (76 mm) since the average foot length for participants in this study was 262 mm. Participants climbed the ladder several times prior to data collection so that they became comfortable with climbing the ladder used in this study. In all trials, participants were instructed to climb the ladder at a 'comfortable but urgent pace' in order to simulate the speed at which a person would climb a ladder during a regularly busy workday. For both of the controlled climbing styles, participants climbed the ladder 5–8 times with the spin rung locked in place, and then once when the spin rung could freely spin. This exposed the participant to a low friction rung on both the ascent and descent during the slip trials. Therefore, each participant was subjected to the low friction rung four times over the entire testing session. Between each trial the participants performed a walking task outside the lab so that they were not aware of the spin rung's locked/unlocked configuration.

2.3. Analysis

Slipping outcomes were classified based on the kinematics of a marker placed on the subjects' toes. A trial was considered to be a slip if the foot completely slipped off of the spin rung. Slipping completely off of the rung was determined by the vertical position of the toe relative to the spin rung. If the toe moved posteriorly of the rung and to a lower height than the rung before the contralateral foot had made contact with the next rung, then the trial was classified as a slip. No slipping trials were observed where the subject's foot slipped forward and off of the rung so criteria was not developed for this type of slip. For each slip event, the ascending and descending climbs were considered separately. If a slip was identified during ascent, the descent data were excluded from the analysis since subjects were aware of the rung's slippery condition.

Climbing biodynamics were characterised with climbing speed, double support time, foot forces and body and foot positioning. The foot force variables included the peak horizontal forces, peak vertical forces and the ratio between the peak horizontal and vertical forces. The body/foot positioning variables included the body angle with respect to the ladder, the angle of the foot relative to horizontal and the anterior/posterior positioning of the foot relative to the rungs. All of these variables were calculated using the baseline unperturbed climbing trial that preceded the perturbed (induced slip trial) to ensure that they were related to an individual's climbing style and were not influenced by the slip itself.

Climbing speed and foot forces were measured using the rung force data. To calculate the average climbing speed, the distance between the third and fifth rung was divided by the time it took to get between these two rungs. Specifically, the time from foot contact (FC) of the third rung to FC of the fifth rung was calculated using the rung force data. The timing of FC was determined as the first time point when foot forces began to exceed baseline plus three standard deviations (3SD) of the vertical force. The timing of contralateral foot-off (CFO) was determined as the first time point when foot forces fell below the baseline plus 3SD of the vertical force. The horizontal and vertical foot forces were found from the peak force of rungs two, three and five and averaged across these three rungs. The foot forces were normalised to body mass. The force ratio of the feet was determined from the horizontal and vertical foot force to determine if this variable is relevant to slipping as suggested by Bloswick and Chaffin (1990).

Figure 2. Controlled climbing strategies: (A) rungs, (B) rails, (C) restricted toe gap, (D) unrestricted foot placement.

Kinematic variables of interest consisted of the angle of the body, angle of the foot and anterior/posterior position of the foot. Each kinematic variable was parameterised at the time of FC with the slip rung, CFO following FC with the slip rung during the trial preceding the slip trial. The change (Δ) in these variables between FC and CFO was also calculated. Thus, the kinematic parameters measured were: body angle at FC (θ^{FC}_{body}), body angle at CFO (θ^{CFO}_{body}), change in body angle between FC and CFO ($\Delta\theta_{body}$), foot angle at FC (θ^{FC}_{foot}), foot angle at CFO (θ^{CFO}_{foot}), change in foot angle between FC and CFO ($\Delta\theta_{foot}$), foot placement at FC (d^{FC}), foot placement at CFO (d^{CFO}) and the change in foot placement between FC and CFO (Δd). Body angle was measured to represent how close the climbers positioned themselves to the ladder. This angle has been demonstrated to be important for stability during other dynamic tasks such as sit to stand (Pavol, Runtz, and Pai 2004) and slipping (Bhatt, Wening, and Pai 2006). The body angle was measured between the vertical of the ladder and the line segment between the subject's toe marker and centre of trunk (Figure 3A). The centre of trunk was found using anthropometric tables based on the cervical marker and mid-hip joint centres (de Leva 1996). The mid-hip joint centres were found using Bell's Method and the anterior superior iliac spine and posterior superior iliac spine markers (Bell, Pedersen, and Brand 1990). Foot angle and foot placement were variables of interest since slipping occurs at the feet. The foot angle was calculated as the angle between the horizontal plane and a vector from the calcaneus marker to a marker placed anterior to the first toe markers (Figure 3B). The foot placement was calculated as the anterior/posterior distance (*y*-direction, Figure 3C) from the marker placed on the most anterior position of the first toe and the mid-point of the ladder rungs. Foot placement was normalised to participants' foot length. The timing of FC and CFO for kinematic parameters was determined using the anterior/posterior (*y*-direction) and superior/inferior position (*z*-direction) of the toe marker. Position data were used instead of force data since forces were not available on the slipping rung. For ascending climbs, the frames were found when the toe marker's superior/inferior position had a change greater than two standard deviations (2SD) of the average *z*-position during stance on the rung. FC was the first time point that the toe marker of the foot in contact with the fourth rung fell within this 2SD window. CFO was the last time point that the toe marker of the foot contralateral to the FC foot fell within the 2SD window. For descending climbs, the same method was used, except the anterior/posterior position of the toe marker was used instead of the superior/inferior position. Visual inspection showed that these criteria accurately identified the moments of FC and CFO. The double support time was measured as the time difference between FC and CFO.

Fisher's exact test was used to evaluate hypotheses related to slip risk (Hypotheses 1 and 2), while ANOVA methods were used to identify significant differences between climbing biodynamics that led to a slip and those that did not lead to a slip (Hypothesis 3). Fischer's exact test was performed on the perturbed trials with slip outcome as the dependent variable and toe gap restriction, hand positioning, climbing direction and age group as the independent variables. Hypothesis 1.1 would be confirmed if restricted toe clearance was found to statistically affect slip rate. Hypothesis 1.2 would be confirmed if hand positioning was found to not statistically affect slip rate. Hypothesis 1.3 would be confirmed if significantly more slips were observed during descent than ascent. Hypothesis 2 would be confirmed if age group was found to significantly influence slip rate. ANOVA analyses were performed separately for ascending and descending climbs with the climbing biodynamic variables (foot forces, climbing speed, double support time, body positioning and foot positioning) as the dependent variables and slip outcome as the independent variable. Age group was also included as an independent variable in this analysis to control for differences across age groups. Hypothesis 3 would be confirmed if climbing biodynamics were

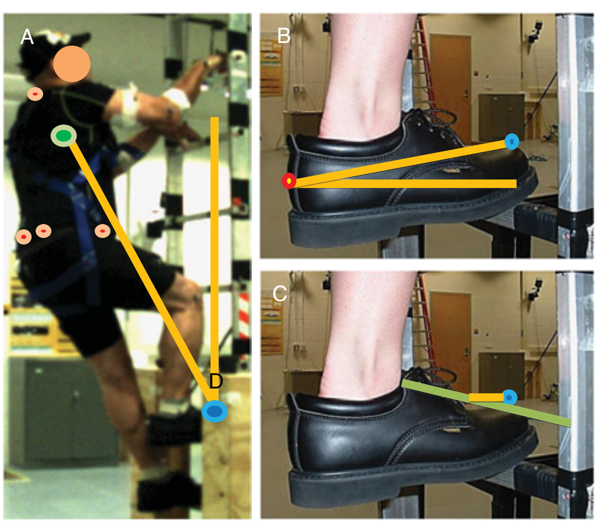

Figure 3. Measurements of body parameters: (A) body angle, (B) foot angle, (C) foot placement.

found to be statistically different in trials that led to slips compared with trials that did not lead to slips. Because only one slip occurred when toe clearance was unrestricted, only data from restricted toe clearance trials were included when testing Hypothesis 3.

3. Results

Participants slipped off of the rung 14 times during the 57 trials where they experienced a low friction rung. Twelve participants experienced at least one slip. Seven slips occurred during ascent and seven slips occurred during descent. Nine slips were with rail hand positioning and five slips were with rung hand positioning. Slipping was over six times more likely with restricted than with unrestricted toe clearance ($p < 0.01$) (Figure 4) confirming Hypothesis 1.1. Slip outcomes were not significantly influenced by hand positioning ($p = 0.31$) (Figure 4) nor by climbing direction ($p = 0.51$) confirming Hypothesis 1.2 but rejecting Hypothesis 1.3. Age group significantly influenced slipping risk ($p < 0.01$) confirming Hypothesis 2 with slips occurring most frequently in the youngest age group (18–24 yr) (20.0%), followed by the eldest group (45–64 yr) (13.3%). No slips were observed in the middle group (25–44 yr) (Figure 4).

Some of the climbing biodynamics variables were significantly different between trials that led to slips compared to those that did not lead to a slip, partially confirming Hypothesis 3. The foot angle at CFO (θ^{CFO}_{foot}, $p < 0.05$) was larger in trials leading to a slip than trials not leading to a slip, when ascending the ladder (Figures 5 and 6, Table 2). Biodynamics that led to a slip during descent were characterised by a longer double support time ($p < 0.05$), a smaller body angle during FC (θ^{FC}_{body}, $p < 0.05$), greater change in body angle ($\Delta\theta_{body}$, $p < 0.05$) and a larger change in foot angle ($\Delta\theta_{foot}$, $p < 0.05$) (Figures 5 and 6, Table 2). Body angle at FC was smaller in the youngest age group than the other two age groups (θ^{FC}_{body}, $p < 0.05$) (Table 2). None of the other biodynamic variables were statistically significant.

4. Discussion

Restricted toe clearance was found to dramatically affect slip outcomes, while hand positioning and climbing direction did not have a strong effect. This study suggests that fixed ladders which constrain a climber's foot placement will increase the climber's probability of slipping. Age group was also found to influence slip risk with the youngest age group at the highest risk followed by the eldest age group. Participants who slipped climbed with different double support time, foot positioning and body positioning than participants who did not slip indicating that certain climbing styles are safer than others.

Toe clearance restriction, which constrains foot placement, had a strong effect on slip outcome. Foot placement for the unrestricted toe clearance condition ranged from 19.9% to 56.1% of foot length (50.82 – 143.08 mm) for ascending and 16.6% to 62.4% of foot length (43.77 – 160.86 mm) for descending. Foot placements for the restricted toe clearance conditions ranged from 4.9% to 34.7% of foot length (13.43 – 83.28 mm) for ascending and 7.9% to 36.1% of foot length (17.49 – 88.30 mm) for descending. Fixed ladders may not always accommodate the range of toe space required to allow for unrestricted climbing. Increased slipping risk was identified in this study when the toe clearance approximated the minimum requirements of MSHA (76 mm). The maximum toe clearance observed in the unrestricted conditions was less than the minimum requirement for OSHA (180 mm). This suggests that the OSHA rule exposes workers to significantly less slip risk than the MSHA rule. Some exemptions to the OSHA rule reduce the required toe clearance to 100–110 mm, which might increase slip risk since it is less than the maximum toe clearance in this study and would therefore restrict the toe clearance in some subjects. The results of this study suggest that individual slip and fall risk could be dramatically reduced in the mining industry by increasing the toe clearance requirement. While the results of this study suggest that the OSHA

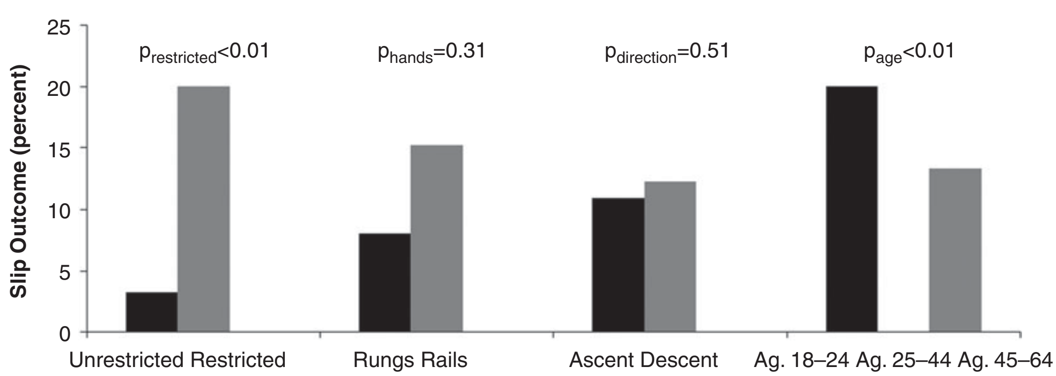

Figure 4. Effects of toe gap restriction, hand positioning, climbing direction and age group on risk of slipping. Numbers represent the percentage of exposures to the slippery rung that led to the foot slipping off of the rung.

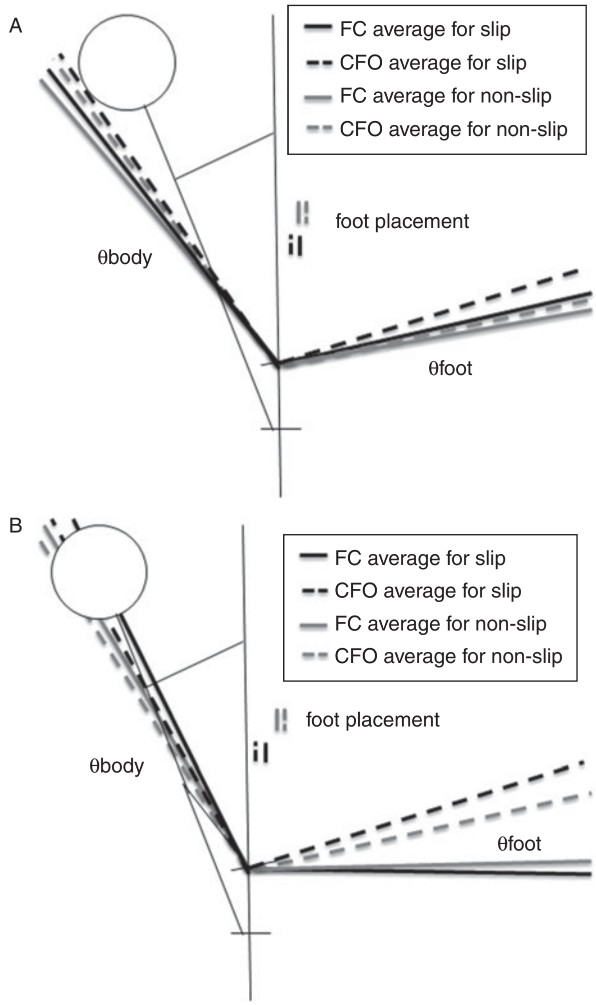

Figure 5. Average body angle (θ_{body}), foot angle (θ_{foot}) and foot placement for slip (black lines) and non-slip (grey lines) climbs at FC (solid lines) and CFO (dashed lines) during (A) ascent and (B) descent.

rule for general industry is sufficient, marine terminal ladders, elevator pit ladders and non-compliant ladders may impede toe space and increase fall risk.

Hand positioning was insignificant to slip outcome. This finding may be because the foot supports most of the load during ladder climbing and low friction was only induced to the feet in this study. Other research suggests that hands may be more relevant to the recovery response after a slip has occurred, rather than contributing to slip risk itself. For example, faster muscle response occur when placing hands on the rung compared with the rail (Paul et al. 2013) and greater break-away strength is achievable when grasping horizontal surfaces rather than vertical surfaces (Young et al. 2009).

Slip risk was significant with age group. The youngest age group (18–24 yr) slipped the most (20.0%) followed by the eldest age group (44–64 yr) (13.3%). These results partially contradict incident rates reported by the BLS reports. The BLS shows that the highest fall rates occur with adults more than 45 years old, which is inconsistent with our study. Possible reasons for this discrepancy might be underreporting of falling incidents by younger employees in industry or that younger employees compensate for increased slip rates with an improved ability to recover from a slip and therefore do not get injured as frequently. The BLS data show a slight dip in fall rates between adults aged 20–24 (incidence rate: 4.9) and 25–34 (incidence rate: 4.2), which is consistent with the drop in falls that this study observed between adults aged 18–24 and 25–44. One possible explanation for the observed V-shaped relationship among age groups and slip outcome may be that inexperience among the youngest age group increases their slip risk, while age-related changes in strength, body mass, coordination and individual biodynamics increase slip risk for the oldest group. While this study did not specifically examine experience as an independent variable, the younger age group is likely to have less ladder climbing experience on average. This lack of experience may have caused them to climb with a non-optimal technique, causing an increase in slip

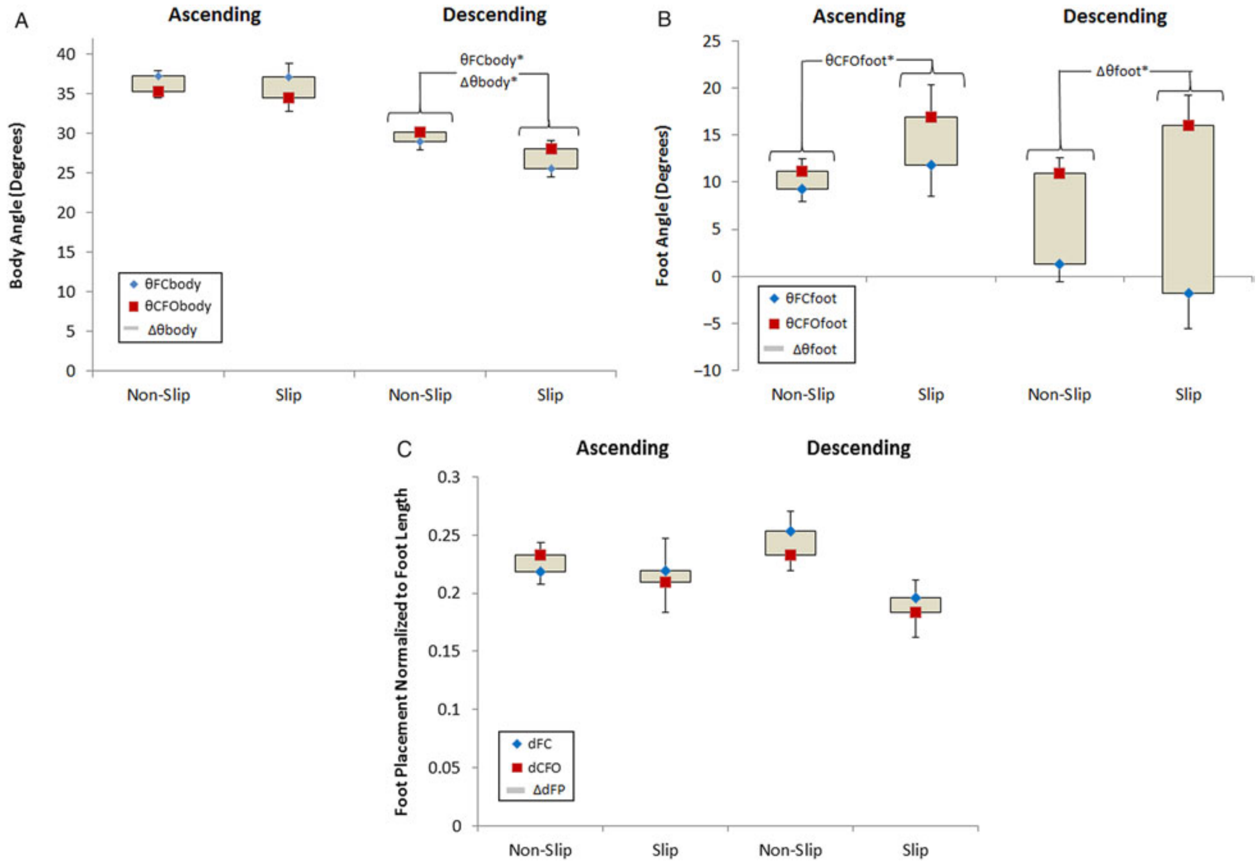

Figure 6. (A) Body angle, (B) foot angle, (C) foot placement at foot contact (FC) and contralateral foot-off (CFO) and change between FC and CFO: ascending (left), descending (right). Foot contact is denoted by the blue triangle. Contralateral foot-off is denoted by the red square. Error bars off the symbol represent the standard deviation of the denoted position. The change in the body/foot parameter is the difference between contralateral foot-off and foot contact. The change is denoted through the grey box.

risk. The increase in slip risk for the older age group is likely explained by a different mechanism. Other studies have also found increased slip risk with older age groups (Moore, Porter, and Dempsey 2009; Moyer et al. 2006; Webster 2000) due to reduced strength, slower response times (Chambers and Cham 2007) and changes to their gait patterns (Moyer et al. 2006). Body mass increased with older age groups, which may also have explained their increased slip risk since mass may be a confounding factor. These mechanisms may have caused increased slip risk in this study although additional research is needed to identify the precise mechanisms that are responsible. Since younger and older age groups are at high risk of slipping, specific attention and training may be most beneficial for these two age groups.

Double support time and body and foot positioning were significantly different between slipping and non-slipping climbing styles, while foot forces and climbing speed were not significant. Those who slipped had a longer double support time and greater change in body and foot angle compared to those who did not slip (Figure 5). Another possible explanation for a longer double support time and greater body and foot angle change may be that subjects who slipped had difficulty supporting their weight while stabilising their foot or body. A larger double support time may indicate that subjects slowed weight acceptance because they had difficulty stabilising their foot or body. Since the foot is the primary supporting load between the ladder and climber, it is critical that the foot can stabilise to accept the climber's weight. Foot stabilisation may be accomplished through the production of ankle plantar flexor moments. The increased changes in body angle may indicate that body movement was not controlled as tightly in climbing styles leading to a slip. Improved ladder climbing training may have potential for improving this control and reducing slip risk.

While more climbing biodynamic measures influenced slipping during descent than during ascent, slip risk was not significantly greater during descent. One factor (foot angle at FC) was significant during the ascent, while four factors (double support time, body angle at FC, change in body angle and change in foot angle) were significant during descent. This suggests that double support time and body and foot positioning may be more important when descending a ladder than ascending a ladder. Descending a ladder may require more precise movement patterns due to impaired visual feedback

Table 2. Mean (standard deviation) on ascending and descending biomechanical parameters during restricted foot placement.

	Slip	No slip	Age group 18–24	25–44	45–64
Ascending parameter					
Speed (m/s)	0.51 (0.08)	0.53 (0.03)	0.53 (0.05)	0.58 (0.07)	0.48 (0.06)
Double support time (s)	0.17 (0.00)	0.17 (0.00)	0.17 (0.00)	0.18 (0.00)	0.17 (0.00)
$\theta_{\text{body}}^{\text{FC}}$ (°)	37.14 (1.68)	37.28 (0.66)	35.42 (1.02)**	38.47 (1.52)**	38.43 (1.25)**
$\theta_{\text{body}}^{\text{CFO}}$ (°)	34.58 (1.78)	35.30 (0.70)	33.31 (1.08)	36.49 (1.61)	36.36 (1.32)
$\Delta\theta_{\text{body}}$ (°)	−2.56 (0.57)	−1.98 (0.22)	−2.11 (0.35)	−1.98 (0.52)	−2.07 (0.43)
$\theta_{\text{foot}}^{\text{FC}}$ (°)	11.85 (3.37)	9.29 (1.32)	8.92 (2.04)	9.95 (3.04)	10.33 (2.50)
$\theta_{\text{foot}}^{\text{CFO}}$ (°)	16.89 (3.48)*	11.12 (1.36)*	10.32 (2.11)	13.70 (3.14)	12.67 (2.58)
$\Delta\theta_{\text{foot}}$ (°)	5.03 (2.43)	1.82 (0.95)	1.40 (1.47)	3.75 (2.20)	2.34 (1.81)
$d_{\text{NORM}}^{\text{FC}}$	0.22 (0.03)	0.22 (0.01)	0.22 (0.02)	0.22 (0.02)	0.21 (0.02)
$d_{\text{NORM}}^{\text{CFO}}$	0.21 (0.03)	0.23 (0.01)	0.24 (0.02)	0.22 (0.02)	0.22 (0.02)
Δd_{NORM}	−0.01 (0.02)	0.01 (0.01)	0.02 (0.01)	−0.01 (0.02)	0.01 (0.01)
VF	0.95 (0.07)	0.99 (0.03)	1.04 (0.04)	0.93 (0.06)	0.94 (0.06)
HF	0.46 (0.04)	0.48 (0.02)	0.49 (0.03)	0.45 (0.4)	0.48 (0.03)
FR	0.49 (0.04)	0.49 (0.02)	0.48 (0.03)	0.49 (0.04)	0.51 (0.03)
Descending parameter					
Speed (m/s)	0.43 (0.06)	0.41 (0.03)	0.42 (0.05)	0.42 (0.07)	0.40 (0.05)
Double support time (s)	0.29 (0.05)*	0.18 (0.02)*	0.23 (0.04)	0.20 (0.07)	0.20 (0.04)
$\theta_{\text{body}}^{\text{FC}}$ (°)	25.55 (1.00)*	29.01 (0.50)*	26.65 (0.79)	29.48 (0.99)	28.69 (0.76)
$\theta_{\text{body}}^{\text{CFO}}$ (°)	28.12 (1.08)	30.13 (0.55)	28.68 (0.85)	30.51 (1.07)	29.93 (0.82)
$\Delta\theta_{\text{body}}$ (°)	2.58 (0.54)*	1.12 (0.27)*	2.03 (0.43)	1.02 (0.54)	1.24 (0.41)
$\theta_{\text{foot}}^{\text{FC}}$ (°)	−1.80 (3.77)	1.30 (1.90)	−0.93 (2.97)	2.31 (3.73)	0.64 (2.87)
$\theta_{\text{foot}}^{\text{CFO}}$ (°)	16.00 (3.24)	10.95 (1.64)	14.16 (2.56)	13.07 (3.21)	9.40 (2.47)
$\Delta\theta_{\text{foot}}$ (°)	17.80 (2.71)*	9.65 (1.37)*	15.09 (2.14)	10.76 (2.69)	8.76 (2.07)
$d_{\text{NORM}}^{\text{FC}}$	0.20 (0.03)	0.25 (0.02)	0.23 (0.03)	0.26 (0.03)	0.23 (0.03)
$d_{\text{NORM}}^{\text{CFO}}$	0.18 (0.03)	0.23 (0.01)	0.20 (0.02)	0.24 (0.03)	0.23 (0.02)
Δd_{NORM}	−0.01 (0.02)	−0.02 (0.01)	−0.04 (0.02)	−0.02 (0.02)	0.00 (0.02)
VF	0.84 (0.07)	0.81 (0.03)	0.85 (0.05)	0.82 (0.06)	0.78 (0.05)
HF	0.39 (0.07)	0.40 (0.03)	0.45 (0.05)	0.36 (0.06)	0.38 (0.05)
FR	0.46 (0.05)	0.49 (0.02)	0.52 (0.03)	0.44 (0.04)	0.49 (0.03)

Note: NORM, normalized to foot length; VF, vertical force; HF, horizontal force; FR, force ratio.
*$p < 0.05$, slip statistical significant; **$p < 0.05$, age group statistical significant.

because your feet are progressing to a rung that is below you and is more obstructed from your vision. Descending may also require more care since energy is being absorbed instead of generated.

Slip risk was not different between ascent and descent. The same number of slips occurred on ascent as descent. The number of slips during descent may have been slightly affected because descent trials occurring after an ascent slip were removed from the analysis. Therefore, future studies that induce a slip during just descent or ascent may be needed to confirm whether climbing direction induces slip risk. Other studies have found the egress process to have a higher injury rate than the ingress process (Moore, Porter, and Dempsey 2009). Contradiction between the present study and the study by Moore, Porter, and Dempsey may also be due to workers in the other study being exposed to vibrations, extended working times and fatiguing work tasks between ascent and descent of the ladder.

The horizontal to vertical foot force ratio proved to be insignificant with regard to slip outcome, which appears to contradict some previous research. Bloswick and Chaffin (1990) suggested that climbers were at risk for forward slipping based on the forward foot forces that were observed during climbing. Yet, subject's feet tend to be inclined during climbing indicating that the forward forces observed during climbing may not actually be friction forces but might instead contribute to the normal force on the surface of the shoe. Therefore, it may be necessary to project contact forces onto the foot as opposed to the ladder in order to infer required friction limits and the slip direction during climbing. One other potential reason that no forward slips were observed is that the footwear used in this study had a raised heel, which may have restricted forward slipping.

Future research may provide additional insight by considering additional ladder types, additional degrees of toe clearance restriction and more specifically identifying the underlying causes for the age effects. This study only considered a single vertical ladder design. Additional research is needed to determine if the conclusions of this study also apply to extension ladders, step ladders and ladders with different rung and rail designs. While this study identified that toe clearance restriction was a critical factor, not enough degrees of toe clearance restriction were considered to precisely identify the threshold where restricted toe clearance increases slip risk. Lastly, this study identified that slip risk was highest in the youngest age group (18–24 yr) and second highest in the oldest age group (44–64 yr). Future research that quantifies which factors that are related to age (experience, strength, reaction time, body mass and climbing style) are most relevant to slipping may provide insight into the underlying causes by which age influences slip risk.

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