Effects of Foot Placement on Ladder Slip Outcomes

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INTRODUCTION

Ladder-related falls are the leading cause of disabling falls to lower levels [1]. Employees injured from ladder-related falls miss an average of 15 work days [1]. Rung shape, orientation, and friction are important factors in generating hand forces and have been deemed important for a safe ladder design [2]. However, ladder climbing is a full body activity and few studies have considered the role of the lower body during slipping. Understanding the effects of climbing technique on ladder slip and fall risk is critical to training safe ladder climbing. Since the foot is the primary load-supporting interface between the ladder and the body [3], foot placement may be a critical variable for estimating slip and fall risk. This study investigates the effects of foot placement on frequency of ladder slips and falls and the kinematic variables involved with slip outcome.

METHODS

The study included 32 participants aged 18-65 with 10 females. IRB approval and written informed consent were obtained prior to testing. Exclusion criteria included musculoskeletal and neurological disorders, pregnancy, and balance disorders. All participants were equipped with standardized attire, footwear and a safety harness. Forty-six reflective markers were placed on anatomical landmarks of the participant and were tracked during each trial (100 Hz). Participants climbed a vertical 12-foot ladder equipped with five reflective markers. Lockable bearings were applied to the fourth rung so that it locked during non-slip trials and spun during slip trials. The safety harness was equipped with a load cell to determine the participant’s weight supported by the harness (1000 Hz).

Each participant was randomly assigned to two of four climbing strategy groups. Climbing strategies included two hand positions (rungs or rails) and two foot placements (mid-foot or forefoot). A board was placed a distance of 25% of the subject’s foot length anterior to the ladder during the forefoot climbing conditions to ensure forefoot placement. Participants were allowed to acclimate to the ladder prior to data collection. Participants were instructed to climb the ladder at a comfortable but urgent pace. For both of the climbing strategies, participants climbed the ladder 5-8 times with the rung locked in place and then once when the rung could freely spin. Between each trial the participants performed a walking task outside the lab so that they were not aware of the rung’s locked/unlocked configuration. The climber’s safety was ensured throughout the testing session with a belayer, spotter, and an impact mat.

A trial was classified as a slip if the participant’s foot completely slipped off the perturbed rung. For each slip event, the ascent and descent were considered as separate samples. A trial was considered to be a slip if the foot completely slipped off of the rung, which was determined by examining the vertical position of the foot relative to the rung. A slip trial was classified as a fall if the load in the harness supported more than 10% of the participant’s body weight. The foot-floor angle was calculated using markers placed on the toe and heel. An ANOVA analysis was performed with age, climb direction, foot placement and hand position as independent variables and with slip outcome as the dependent variable. Because of the low number of fall outcomes, a separate ANOVA analysis was performed with just foot placement as the independent variable and fall outcome as the dependent variable. ANOVA analyses were performed with foot kinematic variables as the dependent variables and foot placement climbing strategy and slip outcome as the independent variables. Foot kinematic variables include foot positioning and foot angles at foot contact time and
contralateral foot-off time. The change in foot positioning and foot angle between foot contact and contralateral foot-off times were also analyzed.

RESULTS AND DISCUSSION

Participants slipped off of the rung 16 times and fell five times during the 64 slip trials. Seven slips occurred during ascent and nine slips occurred during descent with two and three falls, respectively. Ten slips were with rail hand positioning and six slips were with rung hand positioning. Out of the five falls, four were under the rail hand placement condition. Slipping was seven times more likely with forefoot than mid-foot placement (p<0.01) and falls occurred exclusively with the forefoot placement (p<0.01). Therefore it may be determined that forefoot placement puts a climber at greater risk of slipping and falling.

Age group was a significant factor for slipping (p<0.05) with the most occurring in the youngest age group (ages 18-29) (7.8% slips), followed by the eldest group (ages 50-65) (3.1% slips) and then the middle group (30-49) (1.6% slips). This suggests that the younger and older age groups are more susceptible to slipping. One possible explanation for this V-shaped relationship may be that experience and age-related changes in strength, coordination and climbing style affect slip risk.

The rung position relative to the toe and normalized to foot length was 0.27 at foot contact and 0.21 at contralateral foot-off for the forefoot condition while it was 0.45 at foot contact and 0.49 at contralateral foot-off for the mid-foot condition. Thus the foot moved posteriorly from foot contact to contralateral foot-off during the forefoot and anteriorly for the mid-foot condition (p<0.01). The forefoot also moved more posterior during slipping trials compared with non-slipping trials (p<0.001). Thus, the perturbed foot started to slip off the rung prior to contralateral foot-off. Climbing on the forefoot led to smaller foot angles at foot contact (p<0.05) and at contralateral foot-off (p<0.001). A larger increase in foot angle between foot contact and contralateral foot-off was observed among participants who slipped compared with participants who did not slip (p<0.05) (Figure 1). The kinematics of the foot may be an important mechanism for understanding the occurrence of ladder slipping. Specifically, participants who slipped had a greater difference between foot contact angle and contralateral foot-off angle, which suggests that stabilizing the foot as it accepts the weight of the body is critical to preventing slips. Foot stabilization may be accomplished through the production of ankle plantar flexor moments or with use of upper body strategies. Confirming these strategies that maintain stability of the foot angle during climbing may assist in preventing ladder slips.

![Figure 1: Foot-floor angle difference between foot contact and contralateral foot-off across foot placement and slip outcome groups. Mid-foot slips were omitted due to a small sample size (n=2).](image)

CONCLUSIONS

The findings of this study provide insight into how ladder slips and falls occur. A slip or fall is more likely to occur with a forefoot placement. Stabilizing the foot during weight acceptance either through upper or lower-body strategies may improve slip and fall outcomes.

REFERENCES


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