Hand and Foot Responses that Improve Ladder Fall Recovery

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INTRODUCTION

Ladder falls are the leading cause of fatal falls [1]. Previous research has revealed that ladder slip and fall risk is associated with the design of the ladder and climbing biomechanics [2, 3]. Furthermore, preliminary studies by our group have noted that the recovery response to a ladder fall event initially prioritizes reestablishing the hands back on to a ladder followed by the feet [4]. However, there is limited knowledge about the variability in the coordination between hands and feet during ladder climbing and in response to a perturbation. The effect of these different hand and feet strategies on recovery is not well understood. Thus, the purpose of this study is to investigate how hand and foot responses to a ladder climbing perturbation affect recovery.

METHODS

Thirty-five (10 female) participants between the ages of 18 and 29 were recruited for this study. Participant safety protocols were taken with IRB approval, written informed consent, and proper climbing attire which included a safety harness that was equipped with a load cell (1000 Hz). In addition, 47 reflective markers were placed on the participant's anatomical landmarks to record their kinematic data (100 Hz).

Participants climbed a vertical 12-foot custom ladder where they experienced a simulated ladder misstep perturbation. The perturbations were initiated using a rung that was unexpectedly released from under the subject's foot and subjects experienced a perturbation during ascent and descent while wearing high friction gloves, low friction gloves and no gloves. Five to eight unperturbed trials occurred between perturbed trials to reduce anticipation effects.

Recovery to the perturbation was measured based on the amount of weight support that the harness provided after the perturbation. A load cell attached in series with the harness rope was used to record the maximum force between the start of and end of fall. The start of the fall was determined based on the start of the perturbation and the end of the fall was determined based on when the pelvis reached the first local minimum in the vertical position [5].

Review of videos was used to categorize the hand and foot responses. When analyzing the hand responses, only the hand that was in motion (in the case of 2 points of contact) or the hand that would move next (i.e., the lower hand during ascent in the case of 3 points of contact) was analyzed. Four hand responses were observed: 1-Hand did not move; 2-Hand continued to the next rung as planned (i.e., moved 2 rungs up during ascent or 2 rungs down during descent); 3-Hand interrupted the planned path of motion and grasped the rung before the intended rung (i.e., grabbed one rung above the starting position for ascent or one rung below the starting position for descent); 4-Hand was in contact at the start of fall, but released the rung momentarily before re-grasping the same rung. Trials where the other hand released the rung and grasped a lower rung were excluded (n=4/171). Three types of foot responses from the perturbed foot were observed. A-hit the ladder rail or rung and fell to a hanging position; B-stopped on a lower rung; C-fell to a hanging position.

An ANOVA was performed to determine the effects of the hand response on harness forces. Because previous research had determined that gender was an important factor in ladder recovery, gender and the interaction between gender and hand response were also included. A second ANOVA was performed to assess the foot responses on recovery. This foot response model also included gender and the interaction. Both ANOVAs used harness force as the dependent variable. A Tukey's HSD post hoc analysis was performed on the hand and foot type responses. These ANOVA models were assessed separately for ascent and descent.

RESULTS AND DISCUSSION

The pathway for hand motions were variable across participants during ascent: 1) the hand did not move in 36% of trials; 2) the hand grabbed the target rung in 28% of trials; 3) the hand interrupted the planned path of motion and landed at the next rung in 13% of trials; and 4) the hand left the rung and came back down on to the same rung in 21% of trials. During ascent, harness force varied across hand response type ($p < 0.05$) and were higher for female participants ($p < 0.001$) but was not affected by their interaction ($p = 0.148$). Harness forces were highest when the hand interrupted the planned path of motion and grabbed one rung above the starting position. (Figure 1).

The pathway for hand motions were also variable across participants during descent: the hand did not let go of the rung in 11% of recoveries; the hand grabbed the target rung in 62% of trials; the hand interrupted the planned path of motion to grasp one rung above the target rung in 16% of trials; the hand let go of the rung and then reestablish position on the same rung in 8% of trials. During descent, harness forces varied with hand response type ($p < 0.01$) and were higher for females ($p < 0.05$) but were not influenced by response x gender interaction ($p = 0.457$). Harness forces were lower when the hand maintained contact with the rung during the entire fall or reestablished position on the rung that was just released than when the hand continued as planned to the next rung. Therefore, maintaining two hands on rungs or reestablishing the hand back to the same rung may offer benefits for ladder recovery during descent.

The response of the foot varied for ascent and descent trials. Specifically, the foot hit the ladder and fell to hanging position in 33% of ascent trials and in 39% of descent trials; stopped on a lower rung in 43% of ascent trials and in 22% of descent trails; and fell to hanging position without hitting the ladder in 22% of ascent trials and 36% of descent trails. Harness force varied between foot response for ascent ($p < 0.01$) and descent ($p < 0.001$) perturbations. In addition, higher harness forces were observed for female participants during ascent ($p < 0.01$) and descent ($p < 0.01$) but no response by gender interactions were observed in either climbing direction ($p = 0.785$ and $p = 0.576$, respectively). Lower harness forces were observed when the foot reestablished placement onto a lower rung than when the foot hit the ladder side/rung and fell off or when the foot never made contact with the ladder. Therefore, the feet are an important component in recovering from a ladder fall event.

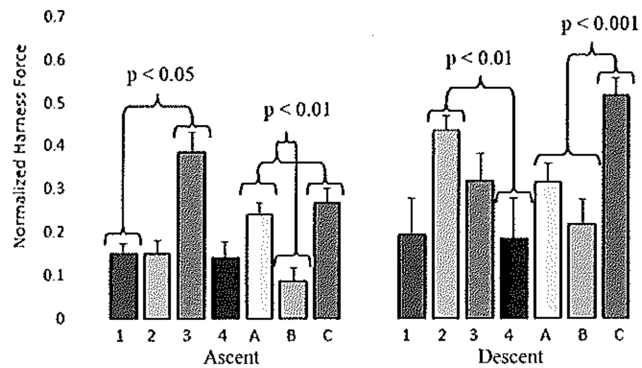

Figure 1: Harness force normalized to body weight for hand (numerical columns) and foot (alphabetic columns) responses during ascent and descent.

CONCLUSIONS

The results of this research indicate that the motion paths of the hands and feet during ladder recovery are important contributors to recovery. Maintaining both hands on the ladder during recovery was effective during ascent and descent. In cases where the hand left a rung, grasping a higher rung (i.e., not interrupting the hand path during ascent and interrupting the hand path during descent) increased recovery. This finding may be explained by previous research that found a more extended arm posture increases upper limb strength [6]. In addition, reestablishing the feet back on the ladder after a fall is critical to recovery. Thus, additional research that identifies means of improving foot placement after a fall may also offer protection against ladder falls.

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