INTRODUCTION

Falls are one of the most frequent work-related events causing fatal injury [1]. In 2011, the use of ladders resulted in 116 fatal injuries [2]. Additionally, non-fatal injuries involving ladders resulted in the most time away from work (a key measure of injury severity) at 14 days [2]. Studies have investigated the role of hand placement and grip strength during unperturbed ladder climbing [3, 4], as well as ladder design and orientation [5]. Few studies have considered ladder climbing as a whole body process or examined the body’s response to a slip while climbing a ladder. This study characterizes the event sequencing of unexpected slips from a ladder and investigates muscle response to a slip. Furthermore, this study aims to identify differences in the response time to a ladder slip when using a rail grasping climbing strategy compared with a rung grasping strategy.

METHODS

IRB approval and informed consent were obtained from thirty-two subjects (10 females) aged 18 to 65. Inclusion criteria required regularly climbing a ladder. Exclusion criteria included: weight over 250 pounds, pregnancy and musculoskeletal, neurological or balance disorders. All subjects were fitted with shoes, athletic clothing and a harness. Forty-six reflective markers and 12 EMGs were placed on the subjects. Bilateral muscles included the vastus laterales, medial hamstrings, anterior deltoids, biceps, triceps, and forearm wrist flexors. A custom, vertically oriented ladder was equipped with a spinning fourth rung, which could be set in a position to freely spin or be secured. Marker position and EMG data were captured at 100 Hz and 1000 Hz respectively, via a Motion Analysis Corporation System (Santa Rosa, CA).

Subjects were randomly assigned to two different climbing strategies with their hands placed on the rung (RG) or rail (RL). A climbing trial consisted of one ascent and one descent of the ladder. For each climbing strategy, the subject performed 5 to 6 unperturbed trials, with the slip rung locked in place and then one trial with the slip rung allowed to freely spin to induce a slip or fall. In-between trials the subjects performed a fatigue walk outside of the lab so they were unaware of status of the spinning rung.

A belaying system (including: belayer, spotter, harness and impact mat) was used to ensure safety of all participants. Slips were defined as when the foot completely slipped off the slip rung during a perturbed trial. Slips and falls were analyzed with respect to their unperturbed baseline trials.

Events during climbing such as foot contact and foot off were identified by tracking the vertical position of markers attached to the foot during climbing. A second order, high pass Butterworth filter, with 10 Hz cutoff frequency, was applied to the electromyography (EMG) data. After filtering, root mean squared (RMS) signal smoothing was performed with a time constant of 30 ms. The resulting RMS signals for each trial were then normalized to maximum activity from baseline climbing. For each climbing strategy, the normalized RMS signals of the unperturbed trials were averaged together to provide mean and standard deviation baseline muscle activity. Muscle response onset was identified when the slip EMG activity exceeded 1 standard deviation of baseline climbing activity for a minimum of 50 ms. An ANOVA was performed to determine the effect of hand placement on the onset of muscle activity after slip initiation.
RESULTS AND DISCUSSION

Of the 64 total perturbed trials, 16 resulted in slips, of which 5 became falls. Ten slips occurred on the rails and 6 slips on the rungs. Four of the 5 falls occurred with a rail hand placement. The average (standard deviation) time of events of a slip trial during ladder climbing were: 0 ms: the foot makes contact with the rung that is allowed to spin freely (the perturbed foot); 153 ms (64 ms): the foot contralateral to the slip steps off of the ladder rung; 218 ms (151 ms): perturbed foot slip is then initiated; 445 ms (196 ms): if there is a hand in motion it makes contact with the ladder; 602 ms (118 ms): the foot contralateral to the slip reestablishes contact with the ladder; 1428 ms (537 ms): the slip foot reestablishes itself on the ladder. Thus, ladder slips typically occur when one of the feet is in motion and all of the weight is being born on the slippery rung. The hands typically grasp the rungs during the initial part of the recovery period and then are followed by the leg contralateral to the slip reestablishing itself on the rung. The last event in the sequence is reestablishing the slip foot back on the rung. While the hands are first to respond to a ladder slip, the recovery process is a full body action, which occurs over a full second duration. Therefore, interventions aiming to improve recovery from ladder slips should consider both the upper and lower body contributions to recovery.

The average delay of first muscle activation onset after slip initiation for all the slip trials ranged from 192 ms to 465 ms. A shorter delay occurred between slip initiation and first muscle activation onset for rung hand placement at 195 ms (97 ms) than rail hand placement at 357 ms (222 ms) (p<0.001), Figure 1. One possible explanation for this reduced response time is that participants may not have perceived the slip as quickly when holding rails because feeling a force tangential to the hands may be more difficult to detect than forces normal to the hand surface. For all of the slip trials the average delay between contralateral foot step off and the first muscle activation was 251 ms. Interestingly, slip trials where participants recovered had an onset of 200 ms (144 ms) while participants who fell had an onset time of 337 ms (46 ms) (p<0.01), Figure 1. Therefore, a slower onset time was associated with reduced ability to recover.

CONCLUSIONS

This study suggests that ladder slips typically initiate when one foot bears most of the body’s weight. The recovery strategy is characterized by initially resetting the hands on the ladder and then resetting the feet back on the ladder. Holding on to the rails led to slower response times, which were associated with falling incidents. Therefore, grasping the ladder rungs during ladder climbing may be preferable for recovery from accidents.

REFERENCES


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