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Biomechanical response to ladder slipping events: Effects of hand placement

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ABSTRACT

Ladder falling accidents are a significant, growing and severe occupational hazard. The factors that contribute to falls from ladders and specifically those that influence the motor response from ladder falls are not well understood. The aims of this research were to determine the effects of hand placement (rung versus rail) on muscle activation onset and peak activity timing in response to slipping on a ladder and to sequence the timing of events following slip initiation. Fifteen unexpected slips from 11 experienced ladder climbers were induced with a freely spinning rung under the foot, while subjects were randomly assigned to a rung versus rail hand grasping strategy. EMG onset time and peak activity time from five bilateral muscles (semitendinosis, vastus lateralis, triceps, biceps and anterior deltoid) were analyzed. Results indicated that significantly slower muscle activation onset and peak response times occurred during rail hand placement, suggesting that grasping ladder rungs may be preferable for improving the speed of the motor response. The triceps muscle activated and reached peak activity earlier in the slip indicating that subjects may initially extend their arms prior to generating hand forces. The study also revealed that slips tended to occur around the time that a foot and hand were in motion and there were just two points of contact (one hand and the slipping foot).

1. Introduction

Falls were the second most frequent work-related event causing fatal injury in 2010 (U.S. Department of Labor – Bureau of Labor Statistics, 2011). The number of fatalities due to ladder use in 2011 was over 40% higher than it was in 1992 (U.S. Department of Labor – Bureau of Labor Statistics, 1992, 2011). Ladder fall injuries are severe as indicated by a median time away from work of 14 days in 2011.

The factors that contribute to falls from ladders are poorly understood. Falls *from* ladders result in a plurality of non-fatal ladder falling injuries (Smith et al., 2006) and occur about as frequently as falls *with* ladders (Shepherd et al., 2006). Much of the existing research on ladder falls has focused on falls *with* ladders where a ladder tips over or falls away from a wall (Chang et al., 2004, 2005a, 2005b; Chang and Chang, 2005). Hsiao et al.'s (2008) literature review found that one of the most common causes of falls from ladders is tripping or slipping of the climber (Dewar, 1977), which can occur due to factors such as missteps (Axelsson and Carter, 1995; Dewar, 1977; Hammer and Schmalz, 1992) or slippery rungs (Björnstig and Johnsson, 1992). Other contributing factors associated with slip risk are limited toe clearance and climbing kinematics (Pliner et al., 2014). Yet, the factors that impact the biomechanical response to slipping while climbing a ladder still require additional investigation.

Grasping ladder rails versus the rungs causes significant changes to the biomechanics of climbing and has been implicated in influencing recovery from slipping. Break-away testing, where a handhold is forcibly pulled from the hand while the participant holds on with maximal effort, has revealed that force generation capacity is higher when grasping horizontally-oriented rungs than when grasping vertically-oriented rails (Young et al., 2009; Barnett and Poczynck, 2000). Other researchers have noted that lower peak resultant hand forces are exerted on the rails than the rungs during normal climbing (Armstrong et al., 2008). While significant research has examined the effects of grasping rungs versus rails on different aspects of climbing (grip strength, kinetics during unperturbed climbing, etc.), little is understood about the impact of grasping strategies on the motor response to slipping. A recent study examined the motor response to a handle-impulse test where the upward force of a handle being held by a participant

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was suddenly increased (Hur et al., 2014). However, additional research is needed to characterize the motor response to actual ladder perturbation events while considering climbing techniques (i.e., rung versus rails). Since previous research has indicated that faster motor response times are associated with improved ability to recover from standing or walking perturbations (Marigold et al., 2005; Woollacott et al., 2005), identifying the impact of grasping strategy on response time may be an important step in identifying safe climbing styles.

Ladder climbing requires full body coordination to maintain points of contact using both upper body and lower body. Previous research has indicated an overlap between hand contact and foot contact with the ladder (Armstrong et al., 2009; Bloswick and Chaffin, 1990). The sequencing of events after a ladder slip, however, is not well understood. Research on same-level slipping has revealed that slips tend to be more severe directly after heel contact than during push-off (Strandberg, 1983), which oriented research to examine the factors that influence slipping during the initial period of stance (Beschorner and Cham, 2008; Lockhart and Kim, 2006). Understanding the sequencing and timing of events during ladder slipping is critical for orienting future research and targeting proposed interventions.

The purpose of this study is twofold: (i) to quantify the effects of hand placement (rung versus rail) on the muscle activation onset and peak activity timing in response to ladder slips, and (ii) to determine the sequencing of muscle activation times. We hypothesize that grasping the rung will lead to different muscle activation onset times in comparison to grasping the rail. Additionally, this study aims to quantify the timing of the slip relative to climbing events and to sequence the reestablishment of hand and foot contact on a ladder after a slip.

2. Methods

2.1. Subjects

Fifteen slips, which were collected from 11 experienced ladder climbers, were analyzed in this study. The data were taken from a larger study of 32 participants (Pliner et al., 2014) and part of the results of this study were previously published in proceedings for a scientific conference (Paul et al., 2013). Only perturbations where the foot completely slipped off of the rung were included in order to focus this research on severe ladder slips. In addition, one subject who slipped was excluded because her climbing style was fundamentally different from the climbing styles of the other subjects (i.e., subject put both feet and both hands on each rung before ascending to the next rung whereas all other subjects alternated their feet on each rung). Subjects that were included in this analysis were between the ages of 18 and 61 (7 male, 4 female) and were recruited from industry sectors where ladder climbing is common, including roofing, firefighting and divers. To qualify as an experienced climber, potential participants needed to reply "yes" to a question that asked if they climbed ladders regularly. Exclusion criteria included weight over 113.4 kg, pregnancy, and musculoskeletal, neurological or balance disorders or injuries that would influence or prevent ladder climbing. Testing was approved by the University of Wisconsin–Milwaukee Institutional Review Board and informed consent was obtained from every subject.

2.2. Procedures and data collection

Subjects were fitted with shoes, athletic clothing and a safety harness. Forty-six passive reflective markers were placed on anatomical landmarks of the subject including the toes (dorsal side of shoe tips), the heels and the third metacarpal joints. Electromyography (EMG) recordings from five muscles were collected bilaterally using 10 double differential electrodes (Trigno®, Delsys Inc., Boston, MA) with a built-in bandwidth filter (20–500 Hz). Bilateral muscles of interest included: biceps, triceps, anterior deltoid, semitendinosus and the vastus lateralis. The upper extremity muscles were consistent with the upper-arm muscles that respond to a handle perturbation (Hur et al., 2014) and the lower extremity muscles were consistent with those that respond to ground-level slips (Chambers and Cham, 2007). Prior to electrode placement, the skin was cleared of any excess hair and cleaned with an alcohol prep pad. The electrodes were placed parallel to the muscle fibers over the muscle belly, per the manufacturer's instructions (Delsys, 2014). EMG signals, sampled at 1000 Hz, were checked prior to testing to ensure a good quality signal.

Subjects were randomly assigned to two climbing styles based on hand position (rail versus rung) and foot clearance conditions (restricted versus unrestricted), described in Pliner et al. (2014). For the restricted toe clearance condition, a wood board was placed at a distance of 25% of the subjects' foot length from the rung on the side of the ladder opposite to the subject. Most of the slips occurred during the restricted toe clearance condition and, therefore, this variable is not considered further in the present study. A belaying system, including a belayer, spotter, harness and impact mat, was used to ensure subject safety. The ladder consisted of 12 rungs placed 300 mm apart (United States Occupational Safety Health Administration, 2003). The fourth rung from the bottom was encased in lockable bearings so that it could be locked in place for non-slipping trials or allowed to freely spin for slipping trials. To establish a baseline for each climbing strategy, the subjects performed 5–6 non-slip climbing trials with the fourth rung locked in place. One perturbed slip trial was then conducted with the fourth rung allowed to freely spin. The subject then switched to the second assigned climbing style, completed an additional set of 5–6 baseline trials, and then experienced a second slip. The subjects were unaware of the status of the lockable rung throughout the test session. Also, subjects could slip during ascent and descent. A 13 camera Motion Analysis Corporation system (Motion Analysis Corp, Santa Rosa, CA) acquired marker position data at 100 Hz, which were time-synchronized with the EMG data.

2.3. Data analysis

Data from at least 3 unperturbed trials were used to quantify the baseline muscle activity. Unperturbed trials were only included in the baseline average if they had similar climbing gait patterns as the perturbed (slip) trial (i.e., started on the same foot and had the same hand–foot coordination) since several studies have noted significant inter- and intra-subject climbing styles (Hammer and Schmalz, 1992; McIntyre, 1983).

A root mean square (RMS) signal smoothing algorithm with a 30 ms moving window was applied to the filtered EMG signals for the baseline and slip trials (Albertus-Kajee et al., 2011; De Luca, 1997; Rouffet and Hautier, 2008). Data from each of the baseline trials were interpolated over 1000 data points from foot contact of the slip foot to the next foot contact (i.e., the foot contralateral to the slip). After averaging the interpolated data, the data were interpolated again at the sampling frequency (1080 Hz) between foot contact ($t=0$) and the average climbing cycle time (contact time of the foot stepping on the slip rung to contact time of the foot contralateral to the foot stepping on the slip rung) to get time-series data that could be compared against data from the slipping trial. The perturbed slip trial RMS EMG signal, which was filtered and smoothed using the same methods as the baseline trials, was compared to the baseline average in order to determine when the muscle activation patterns from the slip exceeded baseline activity. The motor patterns from the perturbed trial were not time-normalized to make them directly comparable to baseline time-series data. This approach was used to determine the onset time when muscles switched from their baseline motor patterns to the recovery response motor patterns following an unexpected perturbation (Marigold et al., 2003; Pijnappels et al., 2005; Tang et al., 1998). Muscle response onset time was quantified as the time point after slip onset when the smoothed EMG signal exceeded the average baseline by more than two standard deviations for a period of at least 50 ms, similar to other methods used to assess responses to slips (Marigold et al., 2003). Only muscle activations that occurred at least 30 ms after slip initiation were included due to the time that is required to process sensory information and initiate a motor response. The activation period of interest contained the peak muscle activity in order to focus on the greatest magnitude of the RMS response. Previous research has indicated that the perturbed limb and the non-perturbed limb respond with similar onset times (Marigold et al., 2003; Tang et al., 1998) and preliminary analyses of the data did not reveal significant differences in muscle onset or peak times across sides of the body (i.e., ipsilateral versus contralateral to the slip). Therefore, left and right muscle times were pooled together.

Descriptive analyses were performed to explain the state of the climber at slip initiation and the experimental conditions for these 15 slips. Categorical variables of interest at the time of slip initiation included: if the contralateral foot was in contact with a rung, and if the subject was using 3 points of contact. Additional variables of interest included climbing direction (ascent versus descent) and toe clearance (restricted versus non-restricted toe gap space).

Events (hand/foot contact, hand/foot off and slip initiation) were determined based on kinematic data using the toe and hand (third metacarpal) markers. The events of hand/foot contact were identified based on the first time when the resultant hand/foot speed fell below 10% of its peak speed whereas hand release/foot off were the first time point when it exceeded 10% of its peak speed.

2.4. Statistical analysis

Mixed-methods repeated-measures ANOVAs were used to assess the effects of handhold (rungs versus rails, between-subject factor) and muscle (within-subject factor) on muscle onset and peak activity times. Onset and peak activity times were transformed with a log function to achieve normality. Similarly, the timing of the temporal events during the slip response was assessed using a mixed-methods repeated-measures ANOVA model. The timing of the event was the dependent variable, while the independent variables included a nominal variable of the event category (within-subject factor) and the handhold (between-subject factor). The event categories included the hand detaching from the ladder rung or rail; the hand reconnecting with the ladder rung or rail; the foot contralateral to the slip stepping off of a rung preceding the slip rung; the foot contralateral to the slip being reestablished back on to a ladder rung; the slipping foot falling off of the rung; and the slipping foot being reestablished back on to a ladder rung. Preliminary analyses revealed no differences between ascent and descent in the timing of EMG onset, peak, or event times and therefore, ascent and descent slips were pooled together. In the case that muscle or event was significant, post-hoc Tukey's HSD tests were performed to determine the muscle or event timing sequences that were significantly distinct. A significance level of 0.05 was used for all analyses.

3. Results

3.1. Biomechanical response

Slip EMG activity was found to deviate from baseline activity (Fig. 1A) but the only consistent deviation across subjects was an increase in triceps activity during the slip relative to the baseline trials (Fig. 1B). The handhold technique was found to affect the timing of muscle activation onset ($p=0.038$) and the peak activation level ($p=0.049$) (Figs. 2 and 3).

Specifically, the average time delay between foot contact and muscle onset was shorter for rung placement (446 ± 212 ms standard deviation) than for rail hand placement (726 ± 306 ms) (Fig. 2).

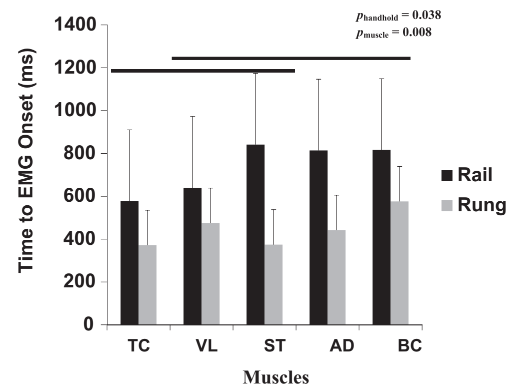

Fig. 2. Average time from foot contact to muscle onset for each muscle, during rail (black) and rung (gray) hand placements. Muscles that are not connected by the black bar are statistically different ($p < 0.05$).

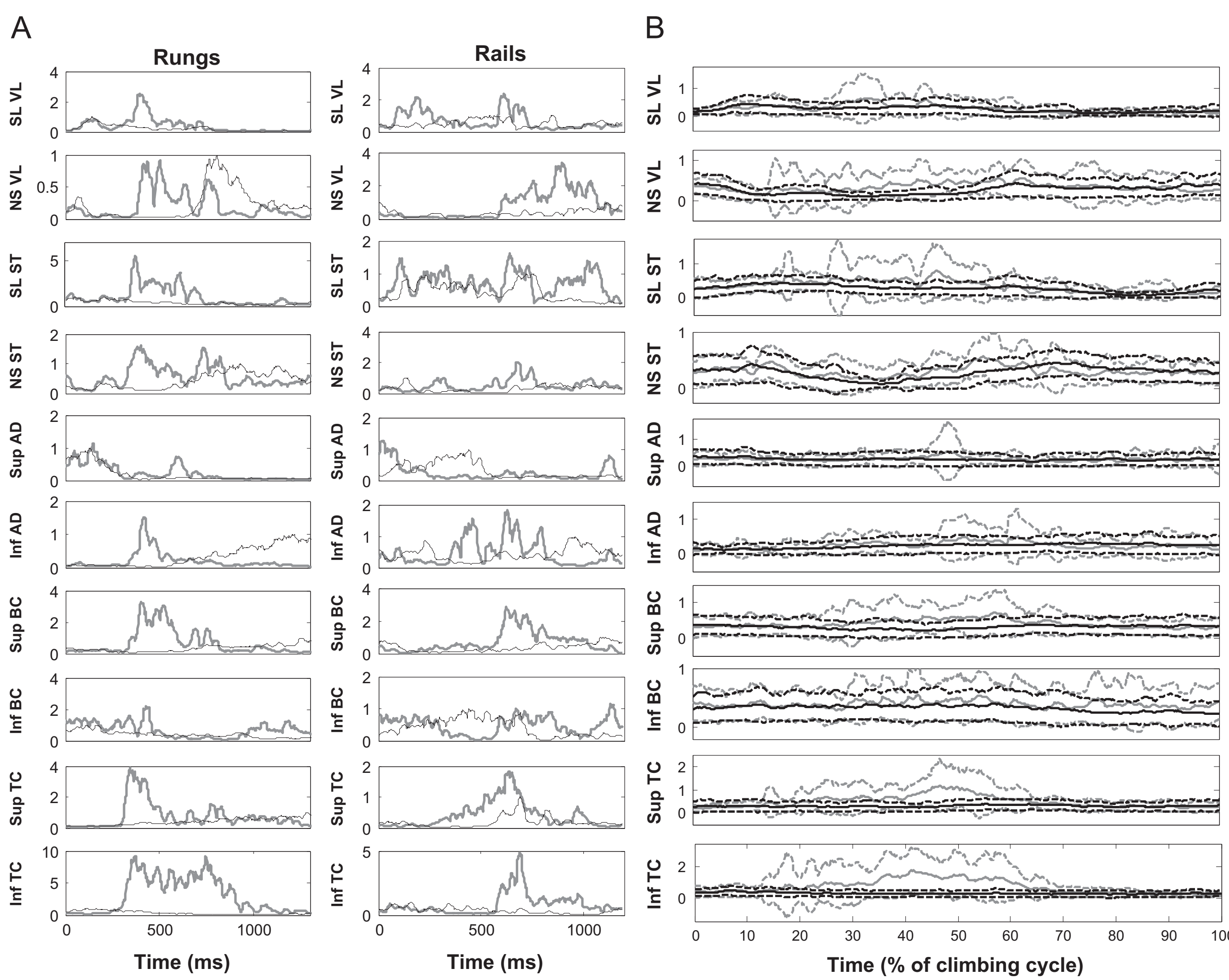

Fig. 1. (A) Representative RMS muscle activity (normalized to the peak RMS muscle activity of the unperturbed trials) from one slip using rung hand placement (left column) and from one slip using rail hand placement (right column). The thin black line represents the average muscle activity of the unperturbed trials and the bold gray line represents muscle activity during the slip trial. (B) Averaged baseline (black) and unexpected slip (bold gray) activity across subjects. The solid lines represent the mean activity and the dashed lines demonstrate ±1 standard deviation from the mean. For the representative and averaged plots, the slip is initiated at time=0. VL=vastus lateralis, ST=semitendinosus, AD=anterior deltoid, BC=biceps, TC=triceps. "Inferior" (Inf) refers to the hand at a lower position relative to the "Superior" (Sup) hand at slip initiation. "Slip" (SL) refers to the slipping leg, while "Non-Slip" (NS) refers to the leg contralateral to the slip.

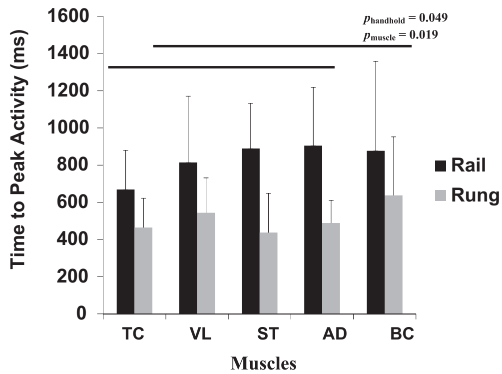

Fig. 3. Average time from foot contact to peak muscle activity for each muscle, during rail (black) and rung (gray) hand placements. Muscles that are not connected by the black bar are statistically different ($p < 0.05$).

Table 1
Subject characteristics.

Subject	Hand placement	Age (yrs)	Height (cm)	Weight (kg)	Foot length (cm)	Gender
1	Rung	50	177.1	82.3	27	M
2 (twice)	Rung	18	167.5	62.2	22	M
3	Rung	22	169	67.8	26	M
4	Rung	18	179	81.4	29	M
Avg (Stdev)		27.0 (15.4)	173.2 (5.7)	73.4 (10.0)	26.0 (2.9)	0 F/4 M
2	Rail	18	167.5	62.2	22	M
5 (twice)	Rail	23	186	111.9	30	M
6	Rail	19	173.5	67.5	26.5	M
7	Rail	45	176	87.3	28.5	F
8 (twice)	Rail	61	155	58.4	25	F
9	Rail	23	176	107.0	26	F
10	Rail	19	170	78.0	26	F
11	Rail	56	167	79.8	27.5	M
Avg (Stdev)		33.0 (18.0)	171.4 (9.0)	81.5 (19.7)	26.4 (2.4)	4 F/4 M
Group						
Avg (Stdev)	4 Rg/9 Rl	32.2 (17.0)	172.4 (8.1)	80.3 (17.0)	26.7 (2.2)	4 F/8 M

Similarly, peak activation times occurred earlier when grasping the rung (518 ± 217 ms) than the rail (816 ± 321 ms) (Fig. 3). Significant differences in onset (p=0.008) and peak activity time (p=0.019) were found across the muscles (Figs. 2 and 3). The triceps onset time (509 ± 205 ms) was earlier than the biceps (718 ± 416 ms) and the anterior deltoid muscles (764 ± 337 ms) (Fig. 2). Peak activity also occurred earlier for the triceps (601 ± 215 ms) than for the biceps (778 ± 427 ms) (Fig. 3). Age, height and weight characteristics (Table 1) were not significantly different between rung and rail hand placement groups.

3.2. Sequence of events

The timing across the different events was found to be statistically different ($p < 0.001$). Post-hoc Tukey HSD test revealed that multiple events were statistically different (Fig. 4). The timing of the slip can be considered in two phases: the time when the foot slips off of the ladder (i.e., the onset of the perturbation) and the time that the limbs reestablish back on the ladder (i.e., the attempted recovery). Typically, the foot slipped off of the ladder around the time when the hand moved off of the ladder and the non-perturbed foot left the ladder. After the slip, the limbs reestablished themselves back on the ladder in the following order: the hand that was in motion, the foot contralateral to the slip and then the slipping foot. The handhold type did not affect the timing of events (p=0.133).

3.3. Descriptive analysis

Subjects varied in their climbing state at slip initiation (Table 2). In 14 of the 15 slips, the slip occurred after the contralateral foot was no longer in contact with the ladder. Only five of the 15 slips occurred when a subject was using three points of contact at slip initiation. Most of the slips were observed during climbing with restricted toe clearance and about half were experienced during ascent.

4. Discussion

The primary goals of this study were to assess the impact of grasping rungs versus rail on muscle activation onset and peak activity timing in response to a ladder slip and to characterize the events that follow a ladder slip. The study revealed that muscle onset times were on average 39% (280 ms) faster when grasping the rungs than when grasping the rails. Slipping typically occurred around the time that both the foot contralateral to the slip and a hand had left their respective rungs, indicating that slips occur when a person has fewer than three points of contact and is most vulnerable.

The faster response experienced while grasping the rungs compared with the rails may be because the motor system was already cued to execute a grasping response while holding on to the rungs whereas a change in grasping strategy was required when grasping the rails. Grasping the rails may require climbers to switch their grip strategy after the perturbation. Armstrong et al. (2009) reported that rail use resulted in a more medially-directed hand force than rung use, which can be generated by hooking the fingers around the outside of the ladder. However, a power grip is required to generate the friction forces required to oppose vertical forces during a fall (Barnett and Poczynck, 2000; Young et al., 2009). The utilization of non-preferred grip strategies has previously been shown to increase response time by up to 200 ms when compared to preferred grip strategies since additional motor planning is required to execute non-preferred gripping (Johnson, 2000). Thus, the change in strategy from a hook grip to a power grip during rail climbing may have required more motor planning and response time. Regardless of the mechanism that causes increased latencies for rail climbing, the degree to which the motor response was delayed (∼280 ms) is substantial. For example, a reduction in postural response latencies of just 28 ms after an agility training program was associated with a 40% reduction in fall events during platform perturbations in stroke patients (Marigold et al., 2005). The increased latency when grasping the rails likely has a negative impact on subjects' ability to recover and may increase fall risk.

The triceps were the first muscle to activate and reach peak activity after slip onset. This response may be analogous to previous research where the response to platform perturbations is characterized by an initial knee extension response followed by knee flexion response (Tang et al., 1998). However, this finding is in contrast to the EMG activities that occur during handle stabilization tasks, where biceps and triceps have been shown to activate around the same time (Hur et al., 2014). Potential reasons for this discrepancy may be due to different objectives by the participants between handle stabilization and ladder fall response tasks. Activating the triceps during a ladder fall event may be needed to extend the arm in order to reach for the next rung. Alternatively, extended arms also increase the potential hand force generation

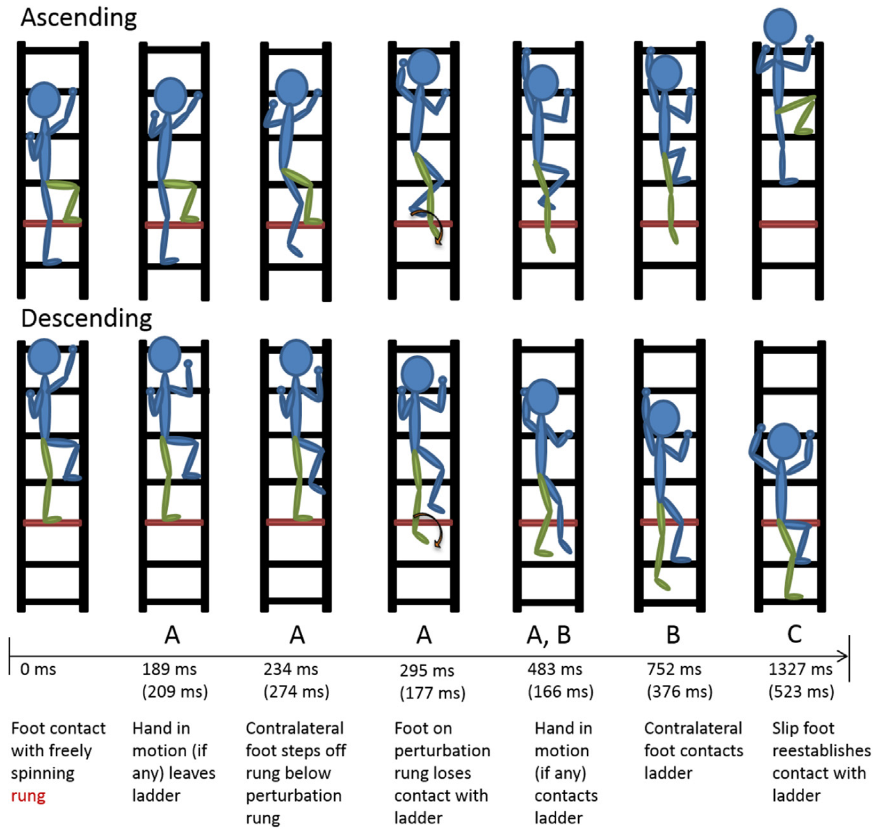

Fig. 4. Timing of events during a ladder climbing slip for ascent and descent. Climbing direction did not affect the timing of events and therefore, only the times averaged across all slips are shown. Timing means (standard deviations) are listed for each event. Events not connected by the same letter are significantly different ($p < 0.05$).

Table 2
Descriptions of ladder condition and climber state at slip initiation.

State of climber at slip initiation	Hand placement	
	Rungs (5 total)	Rails (10 total)
Contralateral foot in contact with rung (no)	0 (5)	1 (9)
Subject using 3 points of contact (no)	3 (2)	2 (8)
Ladder testing condition		
Ladder toe clearance: unrestricted (restricted)	0 (5)	2 (8)
Climbing direction: ascend (descend)	2 (3)	5 (5)

(Salehi et al., 2014). The similar onset and peak activity times between upper body muscles and lower body muscles is consistent with previous research that has shown a rapid, coordinated and concurrent response to slipping between upper and lower body (Marigold et al., 2003).

Another aim of the study was to quantify the timing of events after a slip is initiated in order to characterize the motor response to ladder slips. This study found that most of the slips occurred while both the foot contralateral to the slip and a hand were in motion. Therefore, the slip left the subjects with just one remaining point of contact. This finding supports the utilization of slip-prevention strategies (like three points of contact) around this phase in the climbing cycle.

A few limitations were identified in this study. For example, large standard deviations were encountered for the event timings, which is likely explained by climbing pattern differences across subjects (Table 2). Encouraging consistency across and within subjects may be needed to more precisely identify the sequencing of events and muscles after a ladder slip. Variability may also be partially explained by the lack of control regarding onset of the perturbation. Controlling the perturbation (e.g., through a motorized rung) would have likely led to a more consistent perturbation but would have reduced its environmental fidelity. Additionally, it is noted that while an equal amount of males slipped from the ladder when using rail and rung hand placements, all of the female slips from the ladder occurred during rail hand placement (Table 1). While the sample size was not large enough to test this effect statistically, additional research may be needed to better quantify the effects of gender on ladder recoveries in more detail. Also, not enough slips occurred to power an analysis to determine if EMG onset times or grasping strategies led to differences in recovery rates. Repeating this study with a larger data set would confirm the relevance of response time to recovery risk after slipping from a ladder. Lastly, quantifying differences in motor patterns across different phases of the climbing cycle when aware of a slippery rung versus a non-slippery rung, similar to Cappellini et al. (2010), may provide insights into adaptive strategies used to avoid slipping.

Conflict of interest

There are no known conflicts of interest among the authors of this manuscript.

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