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Lateral Reaching on Stepladders and the Belly Button Rule

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Abstract: A large portion of falls from ladders occur while working from the ladder, including stepladders. Guidelines recommend that the center of mass (i.e. belly button) remain within the rails of the ladder; however, many falls occur because work is performed at an excessive lateral distance from the center of the ladder. Forty-eight participants performed ten lateral reaches of various distances while standing on stepladders of four common heights (6’, 8’, 10’, and 12’). Vertical ground reaction forces were collected by four force platforms – one underneath each ladder foot. The force applied by each of the contralateral rails averaged 11.7% of the total vertical force created by the system during lateral reaches that aligned the belly button with the ladder rail. Maintaining the belly button within the ladder rails generally allowed each ladder foot to remain in contact with the ground, however, reductions in vertical forces under the contralateral ladder feet may be an indicator of excessive lateral positioning and a precursor to increased vulnerability to falls. The “belly button” rule states that the body’s center of mass, as indicated by the location of the belly button or belt buckle, should remain within the rails of the ladder to maintain stability. This study provides empirical evidence to support this rule by examining the reduction in forces underneath the contralateral rails of a stepladder during lateral reaching.

Keywords: ladders, reaching, falls

1. Introduction

In 2010, work-related falls from ladders led to 132 fatalities (Bureau of Labor Statistics, 2012a) and 14,710 injuries that required at least one lost day of work, with the median number of lost days being 25 (Bureau of Labor Statistics, 2012b). Many ladder-related injuries are severe, with 18% requiring hospitalization. The median hospital stay is one week while the duration of disability and unemployment extends to six weeks (O'Sullivan et al., 2004). Ladder safety has become a workplace priority, particularly due to the aging workforce (Diggs et al., 2005). Diggs et al. (2005) reported that 47% of patients hospitalized due to a ladder fall were older than 55 years of age, compared to only 16% of patients who fell from other elevated structures (e.g. window, scaffolding).

Lombardi et al. (2011) conducted a study of injured workers who fell from a ladder and received treatment at an emergency room in order to describe the mechanisms, tasks and conditions related to ladder falls in an occupational setting. The majority of workers (51.0%) reported using a stepladder at the time of the fall. Previous studies have found that the majority of falls from ladders occur while the individual is working from the ladder, rather than during ascent or descent (Axelsson and Carter, 1995; Cohen and Lin, 1991). Lombardi et al. (2011) concurred, reporting that 51.3% of workers interviewed were standing and working on the ladder when the injury-causing incident occurred.

The current American National Standards Institute (ANSI) A14 standard (American Ladder Institute, 2007) states that “the user shall climb or work with the body near the middle of the step or rung.” This recommendation has been specified as the “belly button” or “belt buckle” rule, which states that the center of mass (CoM) of the body, as indicated by the location of the belly button or belt buckle, should remain within the rails of the ladder. It is assumed that if the CoM is within the ladder rails, then the ladder will be stable since the center of pressure of the ladder and individual combined would be within the stability limits defined by the four feet of the ladder. Loss of stability while overreaching may result in falls when either the individual loses balance and falls off the ladder or when the ladder tips over, causing the individual to fall with it.

Lateral weight transfers without a reaching component while standing on a stool (Yang and Aston-Miller, 2005) and the risk of excessive twisting flexibility of ladders (Seluga, Ojalvo, and Obert, 2007) have been investigated, but limited research has focused on the effects of lateral positioning on ladder stability. Reduction of contralateral rail vertical ground reaction forces is an indicator of potential stepladder instability. However, current research does not provide direct evidence relating lateral positioning and stability to support the belly button rule. The purpose of the current study was to analyze and describe the contralateral rail vertical ground reaction forces of a stepladder as a function of the location of the belly button (i.e. CoM) while positioning during a lateral reach.

1. Methods

1.1 Participants

Forty-eight male volunteers participated in a laboratory study. The mean (standard deviation) age, height and weight of the participants was 43.7 (13.4) years, 172.1 (6.1) cm and 87.6 (21.0) kg, respectively. Participants had no self-reported musculoskeletal or balance problems and had normal or corrected-to-normal vision in both eyes.

1.2 Instrumentation

New extra heavy-duty industrial Type 1A fiberglass stepladders of 6’, 8’, 10’ and 12’ were used during the experiment. Taller ladders were heavier and had larger bases of support (Table 1). Ground reaction forces were recorded underneath each foot of the ladder using four 40 cm x 60 cm force platforms (Model # 9286CA, Kistler Instruments AG, Winterthur, Switzerland) sampled at 100Hz and filtered using a zero-lag fourth-order 6 Hz low-pass Butterworth filter.

Table 1. Dimensions (ML = medio-lateral, AP = antero-posterior) and weights of the four stepladders.

Ladder Height	Ladder Weight (kg)	ML Width (m)	AP Length (m)
6’	9.5	0.55	0.98
8’	13.6	0.64	1.27
10’	16.1	0.72	1.62
12’	20.0	0.80	1.91

A 12-camera passive motion capture system (Motion Analysis Corp., Santa Rosa, CA) was used to collect motion data. Markers were placed at the belly button of each participant and the top of the right rail of each ladder. The 3D trajectory data were collected at 100Hz and filtered using a zero-lag fourth-order 8 Hz low-pass Butterworth filter.

1.3 Experimental Procedure

Prior to the experimental tasks, the research team provided sportswear and low-rise trail shoes (Nike Bandolier II) to all participants. A full body harness attached to a belay system was donned to maintain safety of the participants throughout the experiment.

Participants stood on the third rung from the top on the proximal side of the ladder with their feet situated against the ladder rails, which aligned them approximately with their shoulders. For each ladder height, the order of which was randomly presented, participants maintained a relaxed vertical position for 60 seconds to obtain baseline information. Following the baseline trial, ten lateral reaches of differing magnitudes within the reach capability of the individual were performed towards the right side of the ladder. The lateral reaches were intended to vary the position of the belly button (i.e. CoM) within and outside the rail of the stepladder. Participants were allowed to lean their knees against the ladder but were instructed to keep their right arm extended at approximately shoulder height and their left arm relaxed at the side of the body. Figure 1 illustrates the experimental setup.

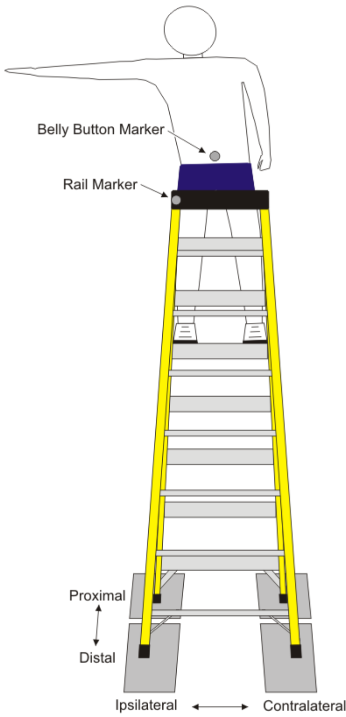

Figure 1. An illustration of a participant standing on the proximal side of the third rung from the top of an 8-foot ladder performing a typical lateral reach. Each foot of the ladder is placed on a separate force platform.

1.4 Data Processing

Belly button distance (BBD), the distance from the belly button marker to the rail of the ladder, was determined and the distance from the belly button marker to the center of the third ladder rung from the top was also calculated in the antero-posterior (BBDAP) direction. Vertical forces under each foot of the ladder were normalized to the total vertical force created by the individual and the ladder combined to account for differences in the weights of the ladders and participants. Linear regression was used to calculate predicted vertical force values corresponding to a lateral reach equivalent to the belly button aligned with the ladder rail. A mixed model (model with both fixed and random effects) with one-way analysis of variance (ANOVA) was used for data analysis in this study. Statistical significance was set at $\alpha = 0.05$.

2. Results

The vertical forces underneath the ladder during quiet standing were not equally distributed among the four feet of the ladder. A higher percentage of force was applied underneath the proximal side of the ladder (i.e., the side the participant was standing on), particularly for the 6’ and 8’ ladders (>60% total force). Participants stood with their belly button more anterior when standing on taller ladders with no significant difference in BBAP between the 10’ and 12’ ladders (Table 2). This result was replicated during the experimental trials with BBAP being larger when the participant was reaching while standing on taller ladders.

Table 2. BBD_{AP} Baseline and BBD_{AP} Reaching for each ladder height averaged across all participants. Note: BBD_{AP} = the distance from the belly button marker to the center of the third ladder rung from the top in the antero-posterior direction.

Ladder Height	BBD_{AP} baseline (mm)	BBD_{AP} reaching (mm)
6’	278 (55)	270 (64)
8’	285 (18)	277 (60)
10’	295 (53)	286 (63)

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12’	294 (50)	287 (61)

2.1 Force Prediction

Figure 2 illustrates the relationship between the contralateral proximal and distal forces obtained and the corresponding BBD for a typical trial. A linear trend line has been superimposed on the graphs, representing the linear regression equation used to determine the vertical force associated with a BBD equal to the location of the ladder rail (i.e. BBD = 0). The predicted forces for the two contralateral force platforms were determined for each participant and ladder height and are presented as a percentage of the total weight of the system (participant and ladder) (Table 3).

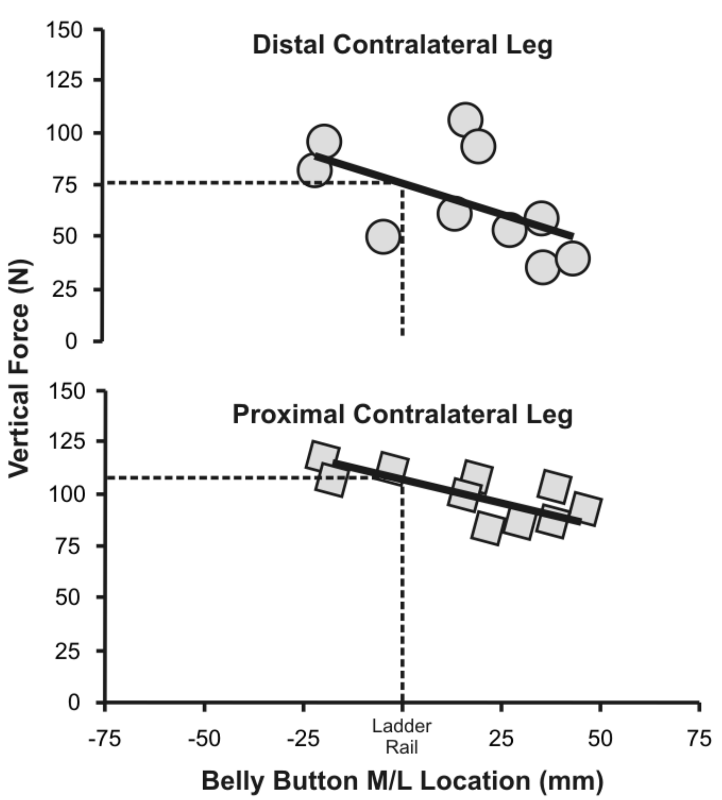

Figure 2. Reach distances and vertical forces for a typical trial. Linear trend line is superimposed over the data to identify vertical force predicted for a given BBD. The dashed lines indicate the vertical force predicted for BBD equal to zero when the belly button is at the same location as the ladder rail. Note: BBD = the distance from the belly button marker to the rail of the ladder. (6’, 8’, 10’ and 12’) used in experiment.

Table 3. Mean (SD) percentage of predicted force applied to each contralateral force platform during lateral reaches with the belly button in line with the ladder rail.

Ladder Height	Proximal	Distal
6’	9.6 (6.4)	6.9 (4.6)
8’	13.8 (10.1)	7.8 (6.3)
10’	10.5 (9.6)	15.5 (8.2)
12’	12.6 (11.8)	17.2 (9.3)

Contralateral distal forces were significantly affected by ladder height when BBD = 0. Forces underneath the 6’ and 8’ ladders were not significantly different, but there was a significant increase in percentage of force under the contralateral distal foot of the 10’ ladder, and a further, statistically significant, increase for the 12’ ladder ($p < 0.001$). Proximal forces were not significantly affected by ladder height ($p = 0.104$).

3. Discussion

While standing on a stepladder, tasks located outside the bounds of the ladder rails may tempt workers to perform lateral reaches without first descending and moving the ladder to the proper location. It is unclear how far an individual can reach while standing on a ladder before the system (i.e. ladder and user) will lose stability and tip over. Stability limits for an individual are quantified as a region within the base of support, generally defined by foot placement, to which individuals are willing to displace their center of pressure. Many factors affect the size and shape of this region including age (King, Judge, and Wolfson 1994), load carriage (Holbein and Redfern 1997), foot placement and strength (Holbein and Chaffin 1997). No literature was found regarding stability limits of individuals while standing on ladders, although the “belly button” rule is a commonly used guideline that recommends maintaining the location of the CoM, represented by the belly button, between the rails of the ladder.

Determining stability limits for a system consisting of an individual and a ladder is a difficult task. The base of support of the system is that which is created by the feet of the ladder; however, the interface between the individual and the ladder (i.e. foot placement) must also be considered. If the belly button rule is adhered to during a static task, then the center of pressure of the system will be within the base of support created by the ladder which, theoretically, maintains a stable system. The purpose of the current study was to provide empirical evidence to support or refute the belly button rule by determining the relationship between lateral positioning of the belly button and the forces underneath the feet of a stepladder.

Stepladders may have an equal lateral weight distribution but we found that when an individual was standing vertically on a stepladder, larger forces were measured underneath the feet on the proximal side of the ladder due to the weight of the individual and that of the ladder. Many factors can influence the weight distribution, but generally, the percentages of forces generated underneath the proximal feet of the ladder were higher for the shorter (6’ and 8’) ladders. As shown by the antero-posterior distance of the belly button to the ladder rail, individuals tended to lean forward while standing on taller ladders, shifting the weight distribution forward. The anterior shift in body position more evenly distributes the weight of the system onto the four ladder feet, possibly increasing the stability of the system. This may explain why individuals maintained a forward belly button position while reaching on the taller ladders.

The predicted contralateral vertical forces associated with a lateral reach placing the belly button equal to the rail of the ladder were substantially lower than the baseline trials. On average, there was still some force applied to each of the force platforms, indicating that the ladder feet had not risen off the ground; however, there were individual trials that resulted in a zero vertical force for at least one of the ladder feet. It is crucial for all of the feet of a ladder to maintain contact with the ground. Although a ladder may remain upright with only three feet in contact with the ground, it is more susceptible to tipping over and twisting (Seluga, Ojalvo, and Obert 2007). The lack of force underneath the feet of the ladder can be thought of as a precursor to the ladder tipping over; therefore, the system (ladder and individual) is most stable when the force distribution is close to that during vertical quiet standing. Current data suggest that maintaining the belly button within the ladder rails generally allows each ladder foot to remain in contact with the ground; however, the decline in vertical forces indicates a reduction in the safety margin for the system making it more vulnerable to external factors that may initiate a fall.

The stability of an individual working on a stepladder may be affected by many factors. Working height has been determined to be one of the most influential factors (Yang and Ashton-Miller 2005). In the current study, the percentage of vertical forces associated with the contralateral rails increased with ladder height. This finding does not necessarily indicate that taller stepladders are more stable or less prone to tipping over, but it may provide some insight into the changes in reaching movements employed by individuals at different heights. Generally, the distal contralateral leg of the stepladder is prone to transmitting the least amount of force during a lateral reach. The adjustments in reaching behavior at greater heights (i.e. moving the center of mass forward) increases the force underneath this leg and may account for the larger forces recorded for the taller ladders. Future research is needed to more fully examine how the kinematics of reaching and working on a ladder affect the stability of the individual and ladder system.

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