Correlations between reach, lean and ladder tipping risk

Christopher L. Deschler [a], Erika M. Pliner [a,b,1,*], Daina L. Sturnieks [b,c], Stephen R. Lord [b,d], Kurt E. Beschorner [a]

[a] Department of Bioengineering, University of Pittsburgh, 301 Schenley Place, 4420 Bayard St, Pittsburgh, PA 15213, United States
[b] Falls, Balance and Injury Research Centre, Neuroscience Research Australia, Sydney, NSW, Australia
[c] School of Biomedical Sciences, Faculty of Medicine and Health, University of New South Wales, Sydney, NSW, Australia
[d] School of Population Health, Faculty of Medicine and Health, University of New South Wales, Sydney, NSW, Australia

ABSTRACT

Overreaching is a common cause of ladder falls, which occur frequently among older adults in the domestic setting. Reaching and body leaning during ladder use likely influence the climber-ladder combined center of mass and subsequently center of pressure (COP) position (location of the resultant force acting at the base of the ladder). The relationship between these variables has not been quantified, but is warranted to assess ladder tipping risk due to overreaching (i.e. COP traveling outside the ladder's base of support). This study investigated the relationships between participant maximum reach (hand position), trunk lean, and COP during ladder use to improve assessment of ladder tipping risk. Older adults (n = 104) were asked to perform a simulated roof gutter clearing task while standing on a straight ladder. Each participant reached laterally to clear tennis balls from a gutter. Maximum reach, trunk lean, and COP were captured during the clearing attempt. COP was positively correlated with maximum reach (p < 0.001; r = 0.74) and trunk lean (p < 0.001; r = 0.85). Maximum reach was positively correlated with trunk lean (p < 0.001; r = 0.89). The relationship between trunk lean and COP was stronger than that between maximum reach and COP, denoting the importance of body positioning on ladder tipping risk. For this experimental setup, regression estimates indicate reaching and lean distance of 113 cm and 29 cm from the ladder midline, respectively, would lead to ladder tipping on average. These findings assist with developing thresholds of unsafe reaching and leaning on a ladder, which can aid in reducing ladder falls.

1. Introduction

Ladder fall injuries occur in the domestic setting with incidence rates of 2.13 per 1000 inhabitants/year for older males (Faergemann and Larsen, 2000). In the domestic setting, approximately 50% of ladder falls leading to injuries requiring hospitalization are among older adults (Vallmuur et al., 2016). In addition to experiencing a relatively greater number of ladder falls, older adults spend more time in the hospital, signifying more severe injuries, slower recovery, and greater healthcare costs (Vallmuur et al., 2016). The estimated annual cost of ladder injuries in the United States is $24 billion (US Consumer Product Safety Commission, 2014). The most predominant injuries include sprains/strains, head injuries, fractures/dislocations, contusions, and internal organ failure (Faergemann and Larsen, 2000; Lipscomb et al., 2010; Vallmuur et al., 2016). Therefore, ladder falls are a serious threat to older adults' safety and health.

Straight and step ladders are commonly used in the domestic setting among older adults (Hicks et al., 2021). Inappropriate use can cause these ladders to tip, leading to a ladder fall. Specifically, improper ladder placement, the base of the ladder slipping, and excessive reaching are commonly reported events leading to a falling ladder (Partridge et al., 1998; Shepherd et al., 2006). Among these reported events, excessive reaching has received limited investigation compared to ladder placement and the base of the ladder slipping (Chang et al., 2005; Chang et al., 2004; Hsiao et al., 2008; Simeonov et al., 2013).

Excessive reaching is one of the most common causes of ladder fall injury, accounting for approximately 33% of ladder fall injuries (Partridge et al., 1998). According to American National Standards Institute (ANSI) A14 standard, the ladder user should work with their body near the midline of the ladder (American Ladder Institute, 2007). In addition, the "belt buckle rule" is often used as a guideline for safe ladder use (i.e., the user's belt buckle should remain within the vertical ladder rails).

This guideline aims to maintain the center of pressure (COP), the point where the sum of forces acts, within the width of the ladder (Ronk et al., 2011). As one reaches or leans towards one side of the ladder, the forces under the two ladder feet diverge, causing the COP to shift away from the ladder center. When the COP falls outside of a stepladder base, the stepladder is likely to tip – causing the ladder and user to fall (DiDomenico, 2018). Prior studies have analyzed stability during forward reach and lateral reach on a stepladder (DiDomenico, 2018; Sugama and Ohnishi, 2016), however the same information is not available for a straight ladder, which has different mechanical constraints. While a clear basis exists for reach and lean to influence ladder tipping risk, the underlying relationship between reach, lean and ladder tipping risk has not been quantified empirically. Additionally, further biomechanical research on ladder reach in older adults is needed given their increased fall risk.

The purpose of this study was to quantify the relationships between maximum reach, trunk lean and COP displacement from ladder base center (COP) (metric of ladder tipping risk) during a simulated roof gutter clearing ladder task in older people. It was hypothesized maximum reach, trunk lean and COP to be positively correlated with one another (e.g. greater reach and lean associated with greater COP). If reach and trunk lean are causal factors of COP position, then these events should be temporally related. Therefore, it was hypothesized that the time of maximum reach, trunk lean and COP were correlated.

2. Methods

One hundred and four adults (52 men and 52 women, aged: 72.9 ± 5.5 yrs., height: 1.70 ± 0.98 m, weight: 72.5 ± 13.8 kg, upper limb span: 1.74 ± 0.12 m) were recruited via advertisements, community presentations, volunteer registries, and word of mouth. To meet eligibility, participants were at least 65 years old, lived independently, and were willing to climb a 2.7 m tall straight ladder to clear a simulated roof gutter. Exclusion criteria consisted of use of a mobility aid in the home, neurological disorders, bodyweight above 120 kg, and pain that would inhibit ability to complete the gutter clearing task. Ethical approval was obtained from the University of New South Wales Human Research Ethics Committee. Informed written consent was provided by each participant before participating in the study. Of the 104 study participants, data for four participants were excluded entirely because; force profiles could not be generated (n = 1), participants did not follow task instructions (n = 2 i.e. they climbed to the second rung of the ladder instead of the third), or reach and trunk lean could not be calculated due to obstruction of the motion capture system (n = 1). Partial data were excluded for 13 participants due to; the participant applying a large external force to the roof/gutter leading to inaccurate COP calculation (n = 1), or obstruction of the motion capture system where either reach (n = 2) or trunk lean (n = 10) could not be calculated. Therefore, full data for 87 participants and partial data for 13 participants were available for analyses.

A straight aluminum single section ladder (Gorilla 2.7 m 140 kg Industrial Aluminum Straight Ladder, Gorilla Ladders, Eden Prairie, Minnesota) with a length of 2.7 m, rung spacing of 29 cm, and width of 39.1 cm (outer distance between the vertical side rails), was utilized (Fig. 1). The ladder was attached to the top and bottom (4 points of contact) of a horizontal rail system with sliding rollers that allowed for lateral repositioning of the ladder and prevented the ladder from tipping. The ladder was positioned at an angle of 75.5° relative to the ground in the forward direction, as recommended by NIOSH (Department of Health and Human Services, 2017) and supported by biomechanical studies examining ladder base slip risk (Chang et al., 2005; Chang et al., 2004). Additionally, brakes that were active when the ladder was not being moved prevented lateral motion of the ladder. While the ladder was prevented from tipping, slight tilt (up to approximately 2°, corresponding to 70 mm translation at the top of the ladder) could occur to create a more realistic simulation due to the ladder not being fully constrained at the top support. This lateral tipping failure mode is known as top slip, which occurs when greater friction is demanded than can be supplied at the upper support contact points, leading to a sideways ladder tip (Clift, 2004). Small initial motions can be detected by the user, allowing them to adjust and impede the ladder's motion (Clift, 2004), thus the feedback provided by our apparatus is justified. A load cell (MLA22 Single Point Load Cell S/N 2721272002, MeasureX Pty Ltd., Melbourne, Australia) was attached to each ladder foot to sample force data at 200 Hz (Fig. 2). Tennis balls (64 total) were evenly spaced along a 5.8 m gutter. Additional detail on the experimental setup and design has been previously reported (Pliner et al., 2020; Williams et al., 2022).

Six reflective markers were placed on the vertical rails of the ladders, and the locations of the markers were averaged to calculate the midline of longitudinal symmetry of the ladder. Fifty-one markers were placed on the participant to estimate body positioning with respect to the ladder midline: including the spinous process of the 7th cervical (C7) vertebrae, and bilaterally on the head of the second metacarpals, anterior–superior iliac spines (ASIS), and posterior superior iliac spines (PSIS). A motion capture system (Vicon, Vicon Motion Systems LTD., Oxford, UK) sampling at 100 Hz was used to measure the ladder user kinematics.

Prior to undertaking the gutter clearing task, participants were able to familiarize themselves with the ladder, the sliding system, and the
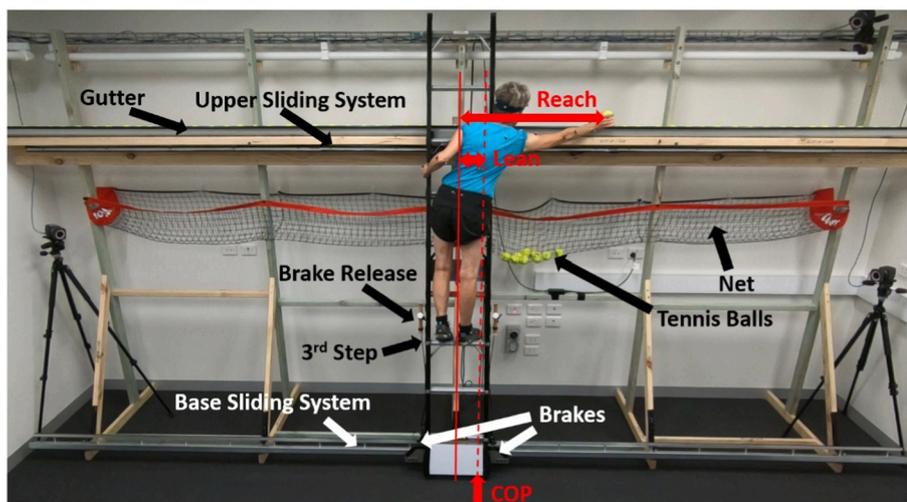
Fig. 1. Experimental apparatus for the gutter clearing task on a straight ladder. The participant was instructed to climb to the third ladder rung to clear tennis balls from the gutter and place in the net below. The upper and base sliding system allowed the ladder to slide left and right, horizontally, and the brake system ensured that the ladder remained secured while the participant was on the ladder. The solid red line indicates the ladder midline and the dashed red line represents the COP displacement while completing the task. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
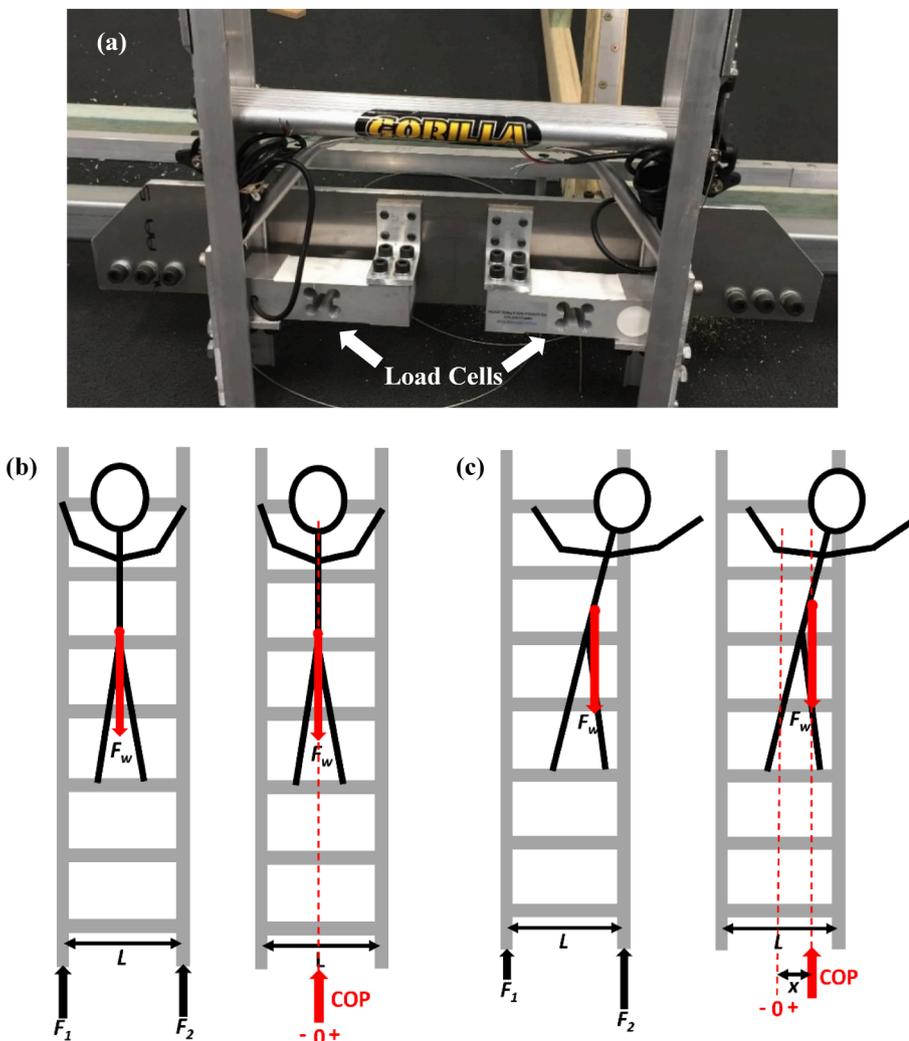
Fig. 2. (a) Two load cells, one attached to the left ladder foot and the other attached to the right ladder foot, were used to collect force data. **(b)** and **(c)** Schematics of ladder and climber with external forces captured by the experimental setup. F_1 and F_2 represent the left and right load cell forces, L represents ladder width and F_w is the weight force of the participant. **(b)** Since F_w is at the center of the ladder, COP displacement equals 0. **(c)** While ladder climber is reaching, the weight force is not centered, and the COP displacement equals x.

brake. Participants were instructed to climb to the third ladder rung and drop all tennis balls from the gutter into the net below, moving the ladder laterally in between climbs, as needed. There was no restriction on the amount of ladder moves that the participant could make to complete the gutter clearing task. Participants were instructed to complete the task "as quickly and as safely as possible" and were not instructed on how to reach and were permitted to use their preferred reaching method.

The maximum reach, trunk lean and COP were calculated for a single reach-to-grasp event for each participant during the gutter clearing task using a custom algorithm (MATLAB, Mathworks, Natick, MA). In addition, the timing of maximum reach, maximum trunk lean and maximum COP displacement with respect to the start of the corresponding climb was extracted. During the gutter clearing task, several reach-to-grasp events occurred for each participant but only one reach-to-grasp event was selected for analysis using the following criteria: 1) the reach-to-grasp occurred when the ladder was positioned in the center of the motion capture volume; 2) the remaining tennis balls to the direction of the reach-to-grasp were outside the participant's grasp (i.e. they were required to move the ladder after their reach-to-grasp to clear the remaining tennis balls from the gutter in that direction). If these conditions were met for both a left and right reach-to-grasp (i.e. the person started with the ladder in the middle of the gutter), the right reach-to-grasp was extracted. A time window for the single reach-to-grasp was visually determined from kinematic and kinetic data to ensure the accurate capture of the maximum reach, trunk lean and COP. Data were

visually reviewed to ensure force profile resulting from ascent and descent were excluded.

The maximum reach distance ("Max reach") was quantified by the farthest mediolateral distance travelled by the marker at the head of the second metacarpal relative to the center of the ladder. The maximum trunk lean distance ("Max lean") was quantified by the farthest mediolateral distance travelled by the trunk center of mass (COM) relative to the midline of the ladder. The trunk COM was calculated from the midpoint between the two hip joint centers and C7 marker (De Leva, 1996) and adjusted for older adults (Hoang and Mombaur, 2015). The hip joint centers were found using Bell's method (Bell et al., 1990) and transformed from the pelvis coordinate system (based on the ASIS and PSIS markers) to the global coordinate system. The maximum COP excursion ("Max COP") was calculated as the farthest lateral distance travelled by the COP relative to the center of the ladder. COP was derived from the forces (F_1, F_2) below the ladder feet and the distance between the rails (L) (Equation (1); Fig. 2) (Williams et al., 2022). Neither motion nor force data were filtered prior to data analysis. Data used in this analysis is a subset of a previously reported dataset (Williams et al., 2022).

$$COP = F_2 * \frac{L}{F_1 + F_2} - \frac{L}{2} \tag{1}$$

Bivariate correlation coefficients were calculated to assess the associations between Max reach, Max lean, and Max COP displacement and timing variables using SAS statistical software (JMP 13, SAS Institute

Inc., Cary, NC). These analyses were repeated as multiple regression analyses that also included gender and its interaction with the other predictor variable (lean or reach) as regressors. Type 1 error rate was set to 0.05 for all analyses in this study.

3. Results

The group mean Max COP measured mediolaterally from the midline of the ladder was 104 mm (SD = 90 mm; Range: −65 to 496 mm). The width of the ladder in this experiment was 391 mm, thus, a COP travelled distance of 196 mm (referenced from the ladder midline), indicates COP positioning outside the ladder siderails. The mean Max reach was 913 mm (SD = 159 mm; Range: 542 to 1386 mm). The mean Max lean was 135 mm (SD = 92 mm; Range: 3 to 443 mm). The mean timing of Max COP, Max reach and Max lean from the start of the corresponding ladder climb was 28.3 s (SD = 10.2 s; Range: 8.5 to 52.2 s), 28.3 s (SD = 10.0 s; Range: 11.9 to 56.6 s) and 28.2 s (SD = 10.3 s; Range: 9.8 to 56.7 s), respectively.

The Max COP was positively correlated with Max reach (r = 0.74; t_{99} = 11.03; p < 0.001) (Fig. 3a). For every 100 mm increase in Max reach, Max COP increased by 44 mm. Max lean showed a positive correlation with Max COP (r = 0.85; t_{91} = 15.56; p > 0.001) (Fig. 3b). The slope of the regression line and correlation coefficient was higher between Max lean and Max COP (R^2 = 0.73) than for Max reach and Max COP (R^2 = 0.56). For every 100 mm increase in Max lean, COP increased by 91 mm. Max reach and Max lean (Fig. 4) were positively correlated (r = 0.89; t_{87} = 18.88; p < 0.001). The slope of this relationship shows that for approximately every 150 mm increase in Max reach, Max lean increased by 100 mm. When analyses were repeated with gender and its interaction with the other predictor variable, no gender main effects or interaction effects are observed (Table 1). For trials with Max COP that could have resulted in ladder tipping (i.e. COP excursion > 196 mm) in cases where the friction forces at the ladder top support and corrective action by the climber were insufficient to avoid tipping, the average Max reach and lean distances were 1127 mm and 291 mm, respectively. The range of Max reach values that would have likely resulted in the ladder tipping (based on COP, Fig. 3) was 949 mm to 1387 mm. This corresponded to Max reaches that were 114% to 150% of an individual's half upper limb span. The range of Max leans that would have likely resulted in the ladder tipping was 202 mm to 435 mm. This corresponded to Max leans that were 12% to 24% of an individual's height.

The time of Max COP was positively correlated with both time of Max lean (r = 0.97; t_{90} = 35.07; p < 0.001) (Fig. 5a) and time of Max reach (r = 0.97; t_{98} = 37.81; p < 0.001) (Fig. 5b). Time of Max reach and Max lean (Fig. 6) showed a strong correlation (r = 0.99, t_{89} = 65.23; p < 0.001). Generally, the time of Max COP, reach and lean coincided; however, few points diverged from this relationship.
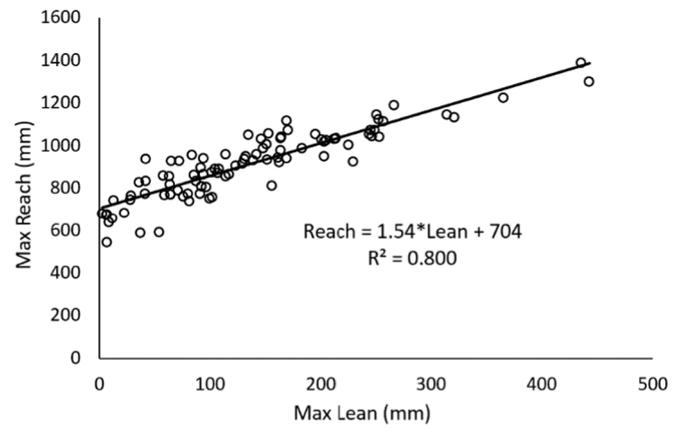

Fig. 4. Max reach plotted with respect to Max lean, with the linear trendline and regression equation shown.

Table 1
Results of the multivariate model including the effect of gender and its interaction on each of the three analyses.

Dependent variable	Predictor variable	F-value	p-value
COP	Max Reach	$F_{1,94}$ = 114.15	<0.001
	Gender	$F_{1,94}$ = 0.37	0.542
	Max Reach × Gender	$F_{1,94}$ = 0.06	0.812
COP	Max Lean	$F_{1,86}$ = 230.42	<0.001
	Gender	$F_{1,86}$ = 0.09	0.761
	Max Lean × Gender	$F_{1,86}$ = 0.47	0.494
Max Lean	Max Reach	$F_{1,87}$ = 339.22	0.001
	Gender	$F_{1,87}$ = 2.15	0.146
	Max Reach × Gender	$F_{1,87}$ = 0.03	0.870

4. Discussion

The reach and lean of an individual working on a ladder influenced the COP, and thus play an important role in ladder tipping risk. This study has shown a stronger correlation between Max COP and Max lean compared to Max reach, suggesting that the lean of an individual working on a ladder is of particular importance to ladder tipping risk. Max reach and lean were linearly correlated suggesting that leaning is part of a coordinated effort during reach-to-grasp task, while grasping a ladder. In addition, the timing of Max COP, reach and lean typically occurred near simultaneously, further supporting an intrinsic relationship between these variables. These results generalized to both gender groups, as gender and its interaction with each of the predictor variables
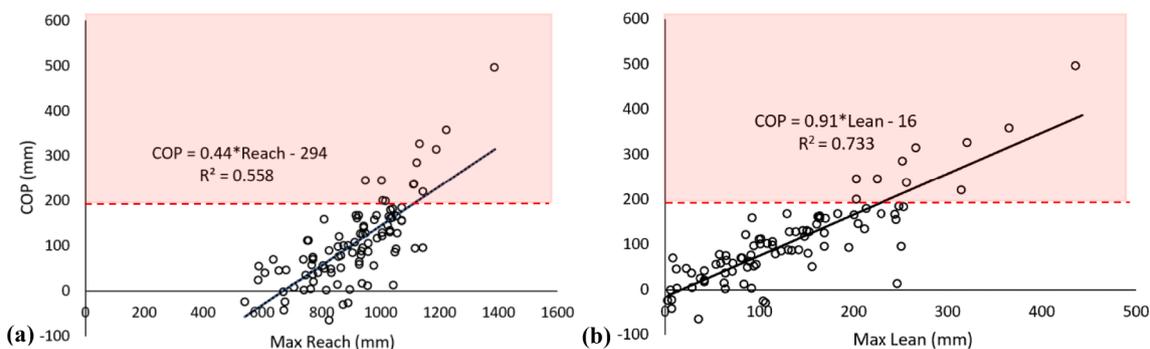

Fig. 3. COP from the center of the ladder was plotted with respect to Max reach **(a)** and Max lean **(b)**. Linear regression lines and equations are displayed on both plots. The red dashed lines represent the ladder tipping threshold (horizontal) defined by COP > 196 mm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
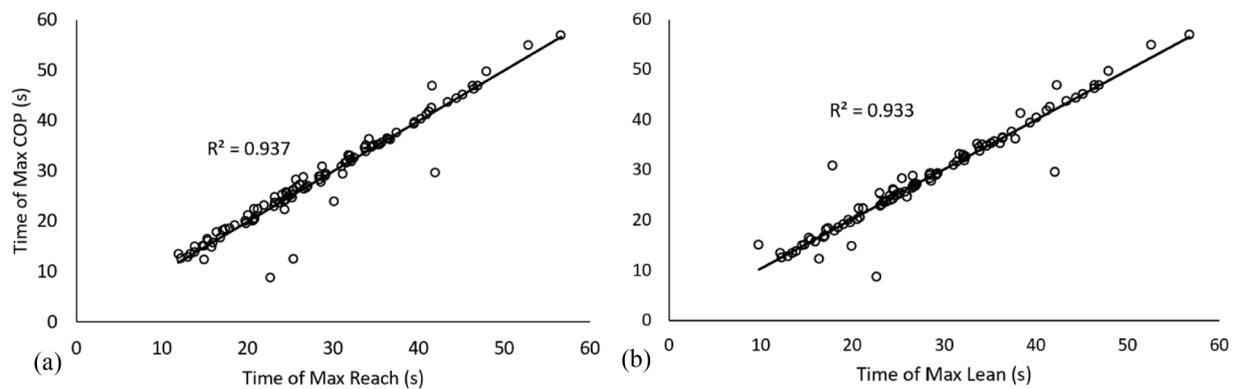
Fig. 5. Time of Max COP excursion during the analyzed climb was plotted with respect to time of Max reach **(a)** and time of Max lean **(b)**.
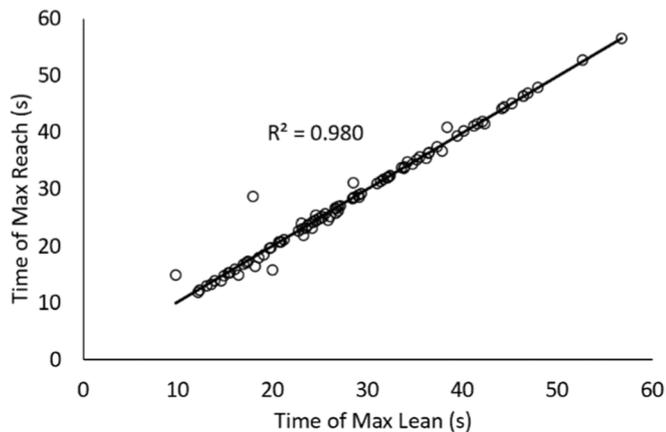

Fig. 6. Time of Max reach was plotted with respect to time of Max lean.

were not significant factors in any of multiple regression analyses.

As expected, an increase in Max reach yields an increase in Max lean, and both increases in Max reach and Max lean increase the Max COP excursion from the center of the ladder. The stronger relationship between COP and lean than between COP and reach is likely because of a significantly higher concentration of mass in the trunk of the human body (~35% total body mass) compared to the upper limb (10% total body mass) (Bruno et al., 2016). The results support the use of trunk positioning messages like the belt buckle rule, to limit COP displacement, as a safeguard to avoid ladder tipping and falls.

The results of this study are consistent with previous research on reaching and leaning. A previous study (DiDomenico, 2018) found that lateral reach leads to an excursion in waist distance away from the center of a stepladder. This excursion leads to an increase in the loaded force on the ladder foot ipsilateral to lean, while causing a decrease in the loaded force on the ladder foot contralateral to lean. This shifting of forces in the direction of lean reflects a shifting in the ladder user's center of mass in the same direction as the lean. These findings are consistent with current results which show that an increase in Max reach was associated with an increase in Max lean, which shifted the Max COP excursion from the center of the ladder. Another study (Chern et al., 2010) analyzed differences in postural control between healthy adults and stroke patients during a reaching task. This study found that in both groups a greater lateral reach distance correlated positively with a greater COP displacement, in line with current results. Analysis on the timing of Max COP, reach and lean during the ladder task further support an intrinsic relationship between these variables. Specifically, this study found the timing of all three variables to typically be near-simultaneous for a clearing attempt to one side of the ladder, advancing and supporting that reach is related to lean and that lean is a

predictor of COP during ladder use. Interestingly, a reach supported by grasping will allow for mechanical freedom that is not present for an unsupported reach task such as reaching while standing, where the person must adopt their lean to prevent center of mass movement outside the base of support. For example, an external hand force effectively extends the base of support, providing additional freedom to reach (Borrelli et al., 2020). Therefore, grasping during reaching while using a ladder may serve as a means of enabling overreaching.

Generally, the time of Max reach, Max lean, and Max COP were consistently aligned although there were some instances where a discrepancy was observed. These mismatches in timing correspond to cases where a different reach-to-grasp attempt was identified as the maximum across different variables. To complete a clearing of tennis balls to one side, the participant may have attempted multiple reach-to-grasp/lean attempts (i.e. reaching laterally and then re-centering on the ladder before reaching laterally again). Occasionally, the timing of Max COP did not occur within the same reach-to-grasp as Max reach and Max lean. However, these events were relatively rare (5.9% of cases had a > 3.0 s discrepancy between Max reach and Max COP timing; 5.5% of cases had a > 3.0 s discrepancy between Max lean and Max COP timing) indicating that these events were typically occurring concurrently.

One possible cause of the differences in COP excursion between participants was how they combined their reach and lean movements. For example, some individuals may have relied primarily on upper limb reaching with minimal leaning, whereas others may have laterally flexed the torso from the waist to lean and increase their ability to clear the gutter. One study based on data from the same experiment presented herein (Pliner et al., 2020) found that individuals who are greater risk takers, based on a risk taking assessment, cleared the gutter in less ladder moves than individuals with a lower propensity for risk taking, presumably due to reaching longer distances. Additionally, trunk kinematics during reaching play a critical role in an individual's ability to reach while standing (Cavanaugh et al., 1999; Damecour et al., 2012; Silfies et al., 2009). Thus, one possible explanation for the variation in reaching within the older population is decreased musculoskeletal function, where limitations in function may influence the favored trunk movement strategies. For example, patients with lower back pain may lack the musculoskeletal control necessary to lean the desired amount (Silfies et al., 2009). Furthermore, within the older adult cohort, differences in the strength of hip, pelvic, lumbar, and thoracic muscles, in conjunction with trunk support strategies, required during standing reach (Damecour et al., 2012) could influence COP excursion. The variation across participants' reaching, leaning, and COP excursions are likely contributed to by a combination of age-dependent factors including risk-taking behavior and leaning ability.

There were some limitations inherent to this study that warrant consideration. Participants were informed that the ladder was secured to the apparatus prior to performing the task, which may have caused some to reach further than in a freestanding ladder condition. Participants

may have been rushing to complete the gutter cleaning task because of prior knowledge that task completion time was recorded. Outside the lab, the conditions may vary, which could impact behavior such as risk-taking. For example, ladders may not be secure which might limit risk taking behavior. Alternatively, there may be factors that contribute to risk-taking, such as reach requirements for a specific task. Here, we studied the risk of tipping based on the user's COP; however, another factor that could resist top slip is the friction between the vertical ladder rails and the top support surface. The results from the regression models may be influenced by the design of the ladder and ladder users. Ladder weight and length would likely affect COP with heavier ladders showing lower sensitivity of the COP to participant reaching. Furthermore, body anthropometry and weight distribution, in particular, would alter the relationship between reach, lean, and COP. Participants who carry more weight in their trunk (i.e., males and obese older adults) (Chambers et al., 2010; Merrill et al., 2019) may show a stronger relationship between lean and COP. Some factors that might influence lean, such as body anthropometry and strength, were not considered in this study. Additionally, the first climb that was within the motion capture volume was analyzed, yet it is possible that participant reach may be associated with the circumstances of the task (e.g. a greater reach during the last climb to grab the final tennis ball). To understand these influences, further analysis is required utilizing data from all climbs.

5. Conclusion

In conclusion, Max COP excursion was positively correlated with both Max reach and Max lean and the timings of these events were positively correlated. Max COP excursion demonstrated a stronger correlation to Max lean than Max reach, thus trunk positioning methods such as the belt buckle rule are good strategies for avoiding ladder tip risk. Reach is an intentional action when completing gutter clearing. When using a straight ladder, it is important to be aware of reach and lean, given their relationship with ladder tipping risk (i.e. the travel of the COP towards and outside the ladder's base of support). Setting limits to reaching might reduce risk of ladder tipping since ladder users may be unable to accurately assess leaning and at what point it might shift the COP outside of the ladder base of support. According to our regression models, an average reaching distance of 113 cm from the midline of the ladder would likely lead to the ladder tipping based on our experimental setup. Similarly, the threshold for ladder tipping would likely be reached at an average lean distance of 29 cm. While these average values provide a mean estimate, variation is present in reach (95 cm to 139 cm) and lean distances (20 cm to 44 cm) that exceed COP stability limits based on our results. Thus, these values are not intended as safety thresholds but simply to describe the fit line. This knowledge may be used to develop ladder safety interventions such as indicators of limits of safe reaching distances (e.g. a physical indicator that extends out from the ladder rails) (Williams et al., 2022). Alternatively, training interventions can be developed to assist ladder users in limiting reach and lean.

CRediT authorship contribution statement

Christopher L. Deschler: Formal analysis, Writing - original draft. **Erika M. Pliner:** Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Writing - original draft, Writing - review & editing. **Daina L. Sturnieks:** Supervision, Resources, Methodology, Conceptualization, Writing - review & editing. **Stephen R. Lord:** Supervision, Resources, Methodology, Funding acquisition, Conceptualization, Writing - review & editing. **Kurt E. Beschorner:** Supervision, Methodology, Writing - original draft, Writing - review & editing.

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