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# Age-Related differences in arm acceleration and center of mass control during a slip incident

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**Arm abduction motion can help reduce lateral center of mass (CoM) excursion and restore balance within the frontal plane during slip perturbations. This study aimed to quantify and compare frontal plane arm kinematics and their relationship with CoM control between older and younger adults experiencing a slip. Eleven older adults (age: 72.0 ± 5.0 years) and eleven younger adults (age: 25.5 ± 6.1 years) underwent an induced slip perturbation while walking. Although peak arm abduction angles were similar between groups, younger adults achieved peak arm abduction significantly earlier (542 ± 67 ms) compared to older adults (853 ± 509 ms; $p = 0.03$). Additionally, younger adults exhibited significantly higher peak arm abduction acceleration compared to older adults (3593.21 ± 1144.80 vs. 2309.83 ± 1428.48 degrees/s$^2$; $p = 0.03$). Younger adults also demonstrated significantly reduced lateral CoM excursion relative to older adults (4.6 ± 3.5 cm vs. 10.47 ± 6.6 cm; $p < 0.01$). Peak arm abduction acceleration negatively correlated with lateral CoM excursion ($r$ = -0.52, $p < 0.02$), indicating that rapid arm movements are associated with improved balance control. A regression analysis confirmed arm abduction acceleration as a significant predictor of lateral CoM displacement ($p = 0.005$) meaning every 1000 degrees/s$^2$ increase in arm acceleration results in an approximate 2 cm decrease in lateral CoM displacement during a slip. These findings suggest older adults' diminished arm acceleration in response to slips potentially compromises their ability to stabilize their CoM effectively, highlighting a possible target for fall-prevention interventions.**

**Keywords** Aging, Falls, Balance, Perturbations, Stability

One of the largest cause of injuries to older adults are from falls, and approximately 25% of adults over the age of 65 will fall on any given year[1,2]. The projected annual cost on the United States' health care system for older adults falling is expected to be $100 billion by the year 2030[3]. Furthermore, it is reported that 12.1% of fall related injuries in women over the age of 65 were from a slip incident, and 17.8% of men over the age of 65 experienced fall-related injuries from a slip, which ranked as a top 3 known contributor to injuries[4]. The majority of the biomechanical research on slip perturbations have focused on the lower extremities[5–20]. There are fewer investigations of the upper extremities during a slip incident as a consequence of focusing on the lower extremity responses[21–29]. It is important to investigate how older adults move their arms as it is shown that moving the arms reduces the likelihood of falling by ~ 70% in younger adults[30].

Slip perturbations can lead to a sideways fall[31] and require extremity movements to restore stability. It is reported that younger adults exhibited up to 54 degrees of lateral trunk flexion during a slip incident[10]. Lateral trunk flexion can be problematic for older adults as hip fractures are known to occur from individuals falling on their sides[32–34]. During a typical slip at heel strike, the perturbed foot slides predominantly anterior and the trailing leg is necessary for regaining balance[35–37]. Furthermore, it is reported that the lower extremities do not produce significant hip abduction during the slip response[16]. As such, the effect of the lower extremities on regaining balance by altering the center of mass may be limited, but may be more effective from a base of support perspective as the foot exhibits lateral displacements up to a few inches during a slip incident[10,38,39].

The upper extremities have been reported to produce three times greater arm abduction angles in the frontal plane compared to the sagittal plane during a slip incident[27]. The arms may be able to control sideways balance by reducing lateral center of mass (CoM) excursion[40], but have no effect on the base of support. In the gecko Hemidactylus platyurus and other lizards, the tails are known to produce rapid movements in one direction to rotate the body in the other to counter undesired angular momentum[41–43]. Furthermore, lizards without

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tails exhibited significantly more rotation compared to lizards with tails during a jumping task[44]. The necessity for a fast swinging appendage may be similar in humans during slip incidents that produce undesired angular momentum[39]. The upper extremities may serve to control lateral center of mass displacements during a slip, similar to appendages of other animals like geckos.

Within the context of the arms, most studies have focused on sagittal plane motions during a slip incident. Arm motions were first described to undergo arm flexion in response to a slip perturbation[21], and since then, additional studies have also reported similar findings[22,23,25]. These studies reported that the arm motions during a slip assisted in controlling the anteroposterior center of mass and reducing trunk extension velocity. The research on the frontal plane motion of the arms during a slip perturbation is limited and has been shown that arm abduction occurs during a slip[27]. Furthermore, the mechanism of frontal plane arm motion was reported to reduce lateral center of mass excursion by 37.5% during a slip incident[40].

Older adults might abduct their arms slower than younger adults when experiencing a slip incident. The left arm movements from initiation to peak shoulder angles in younger adults occur in 250 ms[21,27]. These rapid arm movements require power generation from the deltoid muscles, and the type IIb fibers are shown to decrease in older adults[45]. A decrease in type IIb fibers indicate that older adults may not produce as rapid arm abduction responses as younger adults during a slip incident which may result in a loss of mechanical benefits of arm movements. Studying the arms are important as most physical therapy fall-prevention protocols focus on the lower extremities[46,47]. To date, no studies have examined frontal plane arm motion in older adults during a slip, despite the potential mechanical benefits observed in younger adults during such incidents.

Therefore, the purpose of this study was to examine how frontal plane arm movements and whole-body dynamics contribute to balance during a slip in both older and younger adults. We hypothesized that older adults exhibited significantly decreased peak frontal plane arm abduction angles, lower acceleration of arm abduction responses, and increased lateral center of mass excursion compared to younger adults.

## Results

The purpose of this study was to examine how frontal plane arm movements and whole-body dynamics contribute to balance during a slip in both older and younger adults. We hypothesized that older adults would exhibit (1) significantly decreased peak frontal plane arm abduction angles, (2) lower acceleration of arm abduction responses, and (3) increased lateral center of mass (CoM) excursion compared to younger adults.

### Group differences in arm kinematics

The peak frontal plane arm abduction angle of the contralateral arm to the slipping foot did not significantly differ between younger and older adults (71.97 ± 28.16° vs. 83.32 ± 25.05°, $p = 0.34$; Fig. 1), failing to support the hypothesis of reduced angular displacement in older adults. However, older adults reached peak arm abduction significantly later than younger adults (853 ± 509 ms vs. 542 ± 67 ms, $p = 0.03$), indicating a delayed arm response to the slip.

A 2 × 2 ANOVA (Age × Sex) for peak arm abduction acceleration revealed a near-significant main effect of age, F(1, 18) = 4.20, $p = 0.055$, partial $\eta^2 = 0.189$, suggesting a potentially meaningful difference between younger and older adults. There was no main effect of sex, F(1, 18) = 2.30, $p = 0.147$, partial $\eta^2 = 0.113$, and no significant Age × Sex interaction, F(1, 18) = 0.16, $p = 0.689$, partial $\eta^2 = 0.009$.

### Group differences in arm acceleration and trunk kinematics

Independent-samples t-tests confirmed that peak arm abduction acceleration was significantly greater in younger adults compared to older adults (3593.21 ± 1144.80 vs. 2309.83 ± 1428.48 deg/s$^2$, $p = 0.03$; Fig. 2). No significant differences were found in lateral trunk flexion excursion between groups (17.03 ± 5.28° vs. 16.1 ± 4.5°, $p = 0.66$), indicating that age-related changes in trunk movement may not contribute to lateral COM control in this task.

### Differences in com excursion and slip severity

Younger adults exhibited significantly reduced lateral COM excursion in the frontal plane compared to older adults (4.6 ± 3.5 cm vs. 10.47 ± 6.6 cm, $p < 0.01$; Fig. 3), supporting the hypothesis that older adults experience greater whole-body displacement following a slip. However, no significant age-related differences were found in peak fore-aft heel slip velocity (226.30 ± 62.8 vs. 193.29 ± 74.0 cm/s, $p = 0.27$), suggesting comparable slip severity across groups.

### Relationship between arm acceleration and com excursion

A Pearson correlation revealed a significant moderate negative relationship between peak arm abduction acceleration and lateral CoM excursion ($r = -0.52$, $p < 0.02$; Fig. 4), indicating that greater arm acceleration is associated with reduced COM displacement in the frontal plane.

### Predictors of lateral com excursion

A multiple linear regression analysis was conducted with peak arm acceleration, lateral trunk flexion excursion, peak heel velocity during the slip, age, and sex as predictors of lateral CoM excursion (Table 1). The overall model was statistically significant (F(5, 16) = 6.877, $p = 0.001$), with an R of 0.826 and explaining approximately 68.2% of the variance in lateral CoM excursion ($R^2 = 0.682$, SE = 3.87). Peak arm abduction acceleration was a significant negative predictor (B = − 0.002, SE = 0.001, β = − 0.554, t = -3.274, $p = 0.005$), meaning for every 1000 degrees/s$^2$ increase in arm acceleration, lateral CoM displacement decreased by approximately 2 cm. Sex was also a significant predictor, with male participants exhibiting significantly lower lateral CoM excursion (B = -4.655, SE = 2.090, β = − 0.382, t = -2.227, $p = 0.041$). Age was negatively related but not statistically significant (B = -3.154, SE = 1.962, β = − 0.269, t = -1.608, $p = 0.127$). Lateral trunk flexion showed a marginally significant

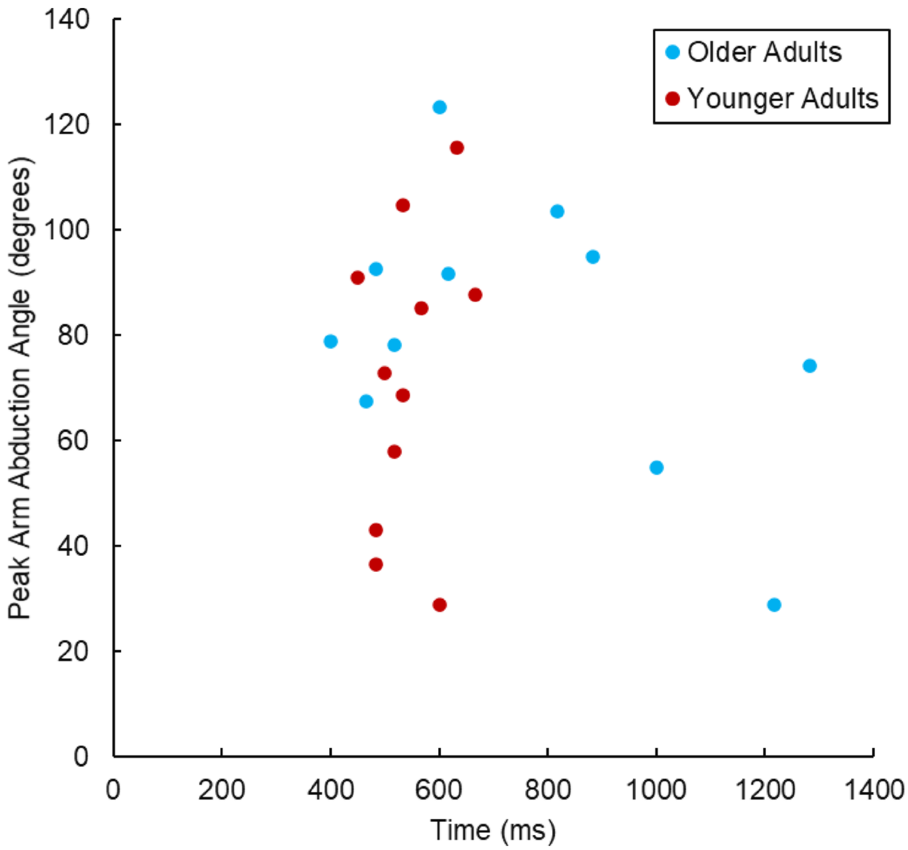


**Fig. 1**. Peak contralateral (to the slipping foot) arm abduction angle and the time to peak arm abduction angle of younger (*n* = 11) and older adults (*n* = 11) during a slip perturbation. The blue points represent the older adults, and the red points represent younger adults.

positive association (B = 0.313, SE = 0.153, β = 0.299, t = 2.049, $p = 0.057$), while peak heel velocity was not significantly associated with lateral CoM excursion (B = 0.012, SE = 0.015, β = 0.142, t = 0.852, $p = 0.407$).

## Discussion

The purpose of this study was to examine how frontal plane arm movements and whole-body dynamics contribute to balance during a slip in both older and younger adults. Contrary to our hypothesis, older adults exhibited a similar amount of peak arm abduction angle compared to younger adults during a slip incident. In support of our hypothesis, older adults exhibited significantly reduced arm abduction acceleration and increased lateral CoM excursion compared to younger adults during a slip perturbation.

The findings of total arm abduction angle in this current study were similar to a previous study reporting the frontal plane motion of the contralateral arm to the slipping foot. In a prior study, it was reported that healthy and young adults exhibited 61.7 ± 26.9 degrees of abduction in the contralateral arm to the slipping foot during a slip incident[27]. Similarly, this current study found that healthy and young adults exhibited 72.0 ± 28.2 degrees of abduction in the contralateral arm to the slipping foot during a slip incident and older adults exhibited 83.3 ± 25.1. Even though peak arm abduction angles were similar between younger and older adults, older adults' peak arm abduction occurred 310 milliseconds after younger adults exhibited their peak arm abduction (Fig. 1). While older adults exhibited similar amounts of peak arm abduction angle compared to younger adults, they differed in the acceleration of their arms achieving peak arm abduction angles.

Younger adults demonstrated significantly greater arm abduction acceleration than older adults, a finding support by both group comparisons and ANOVA results. While the total arm abduction excursion was comparable between age groups, the rate at which the arm abduction occurred was significantly reduced in older adults. This suggests that the protective benefit of the arms may depend on rapid movements rather than excursions. To further illustrate this concept, the lateral COM excursion was significantly greater in older adults than younger adults, and a significant negative correlation was observed between peak arm acceleration and lateral COM excursion ($r$ = -0.52, $p < 0.02$). This finding reinforces the idea that faster arm movements are associated with a reduced whole-body displacement, likely due to the arms creating a counterbalance of lateral trunk motion.

The multiple linear regression model conducted included peak arm acceleration, lateral trunk flexion excursion, peak heel velocity during the slip, and age as predictors of lateral CoM excursion during a slip. Arm acceleration remained a significant predictor ($p = 0.005$), translating to approximately a 2 cm reduction in lateral

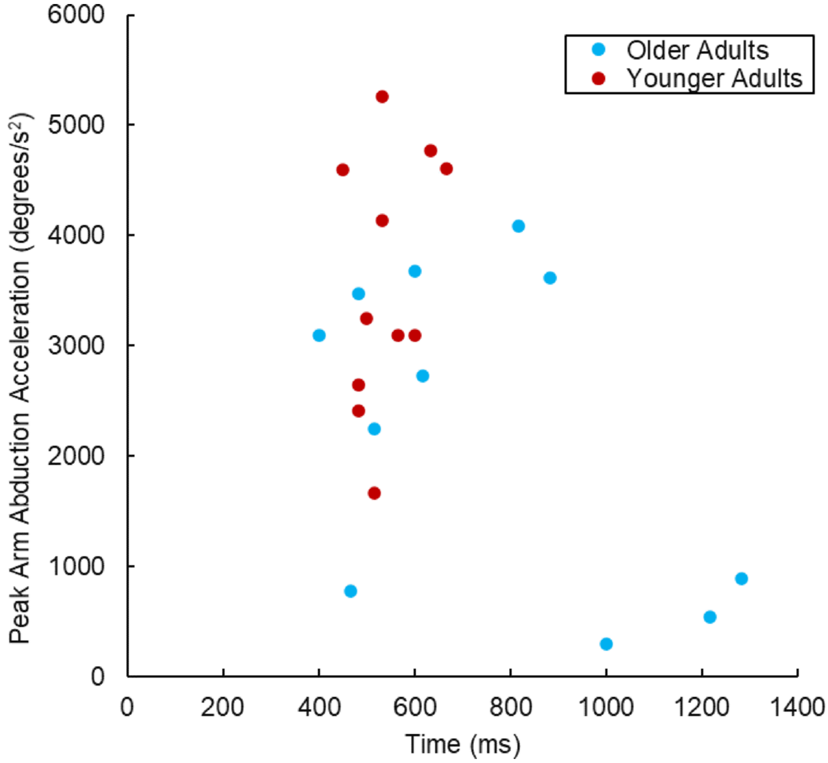


**Fig. 2**. Peak frontal plane arm acceleration and the time to peak arm acceleration of younger ($n = 11$) and older adults ($n = 11$) during a slip perturbation. The blue points represent the older adults, and the red points represent younger adults.

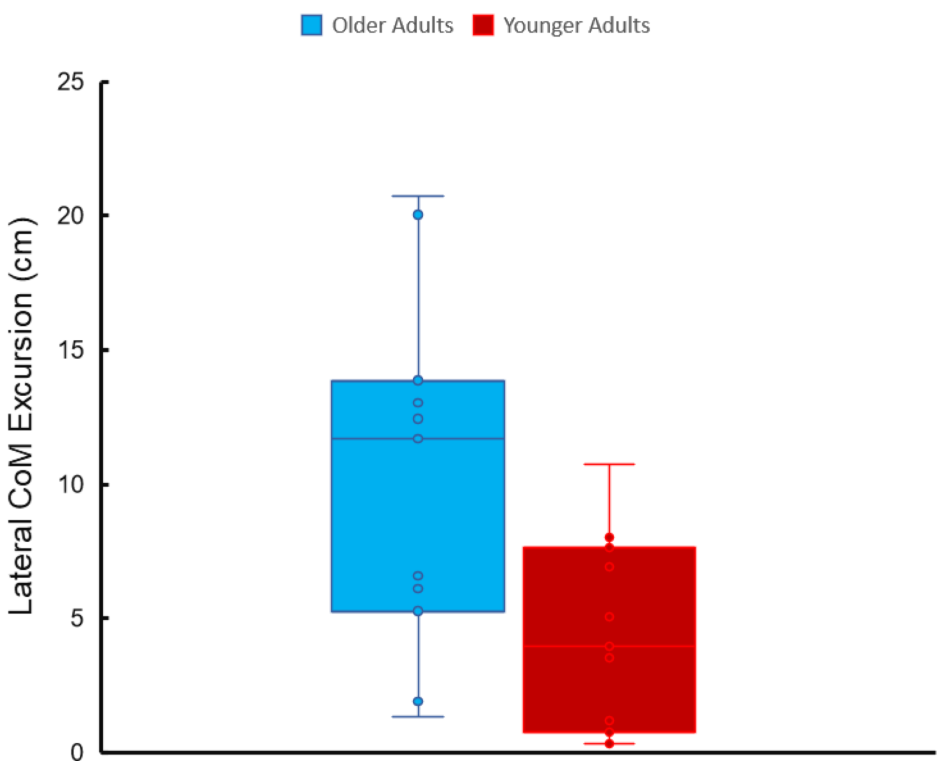


**Fig. 3**. Boxplots showing lateral CoM excursion between old ($n = 11$) and young adults ($n = 11$). Young adults significantly reduced their frontal plane CoM excursion compared to old adults during a slip incident ($p < 0.01$). The horizontal lines represent the median for each group.

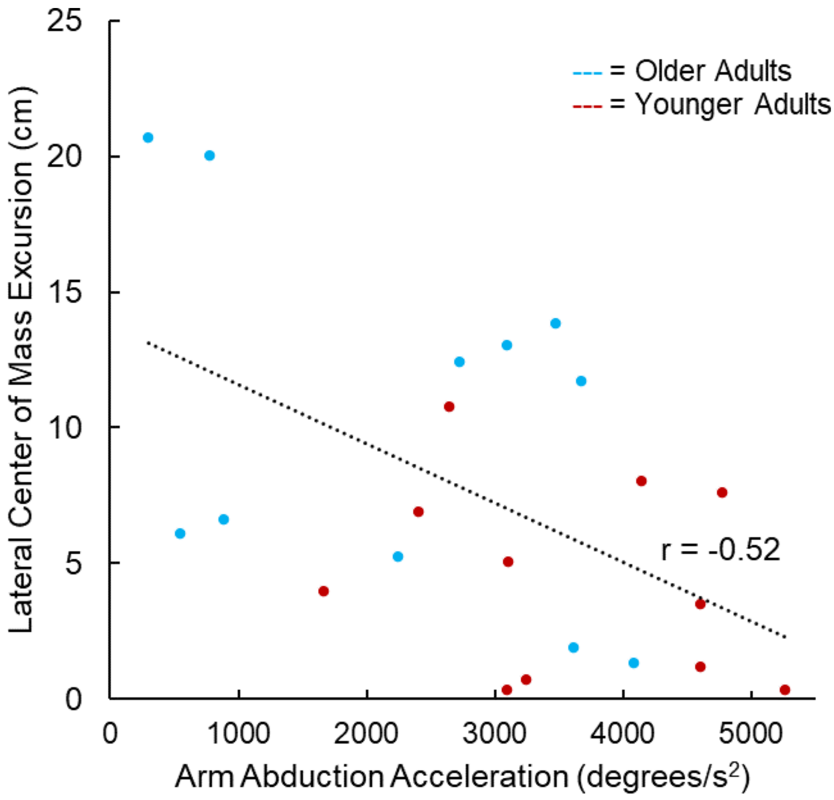


**Fig. 4**. The figure shows a moderate negative correlation between lateral center of mass (CoM) excursion and arm abduction acceleration ($r$ = -0.52, $p < 0.02$). The data points illustrate the relationship between these variables in young adults (represented by red points) and older adults (represented by blue points). The negative trend indicates that higher arm abduction acceleration is associated with reduced lateral CoM excursion and suggests that quicker arm movements may reduce sideways displacement during slip incidents.

| Predictor | B (Unstandardized Coefficient) | SE | t | *p* | B (Standardized) |
|---|---|---|---|---|---|
| Arm Acceleration | − 0.002 | 0.001 | -2.439 | 0.005 | − 0.554 |
| Lateral Trunk Flexion | 0.313 | 0.153 | 2.049 | 0.057 | 0.299 |
| Heel Slip Velocity | 0.012 | 0.015 | 0.852 | 0.407 | 0.142 |
| Age | -3.154 | 1.962 | -1.608 | 0.127 | − 0.269 |
| Sex | -4.655 | 2.090 | -2.227 | 0.041 | − 0.382 |

**Table 1**. Multiple linear regression predicting lateral center of mass (CoM) excursion from Biomechanical predictors.

CoM excursion for every 1000 degrees/s$^2$ increase in arm acceleration. Age was not significant in the regression analysis ($p = 0.127$), while lateral trunk flexion ($p = 0.057$) and heel velocity ($p = 0.407$) demonstrated marginal effects. Although significant differences in peak arm acceleration were found between younger and older adults, the non-significance of age itself suggests that differences observed are not driven solely by chronological age, rather age-related neuromuscular factors such as reduced type II muscle fiber composition[45], decreased neuromuscular coordination[23], or slower central processing speeds that likely influence reactive arm movements and balance control. These findings indicate that age-related differences in slip recovery may be mediated more strongly through rapid arm responses rather than aging itself. This shifts the emphasis from age as a direct risk factor for balance loss towards identifying specific motor deficits as potential targets for intervention in fall-prevention training programs.

Mechanically, the observed relationship between peak arm abduction acceleration and lateral CoM excursion likely reflects a biomechanical mechanism in which rapid arm motion provides a counterbalance to lateral trunk movement during a slip. Arm abduction has been shown previously to reduce lateral CoM excursions during platform perturbations[48], which likely results from swinging 5% of the body's weight[49] in the opposite direction of trunk rotation to reduce CoM excursion from the perturbation.

While the regression analysis revealed that sex significantly influenced lateral CoM excursion ($p = 0.041$), with men showing reduced displacement compared to women, this finding was not explained by differences in

| Participants | Age (years) | Height (in.) | Weight (lbs.) | Sex (M/F) |
|---|---|---|---|---|
| Older adults ($n = 11$) | 72.0 ± 5.0 | 66.36 ± 4.52 | 160.55 ± 32.69 | 6/5 |
| Younger adults ($n = 11$) | 25.45 ± 6.14 | 69.82 ± 4.67 | 168.55 ± 41.68 | 8/3 |

**Table 2**. Participants' demographic and anthropometric information.

arm acceleration as indicated by the nonsignificant sex effect in the 2 × 2 ANOVA. Therefore, it is plausible that factors other than arm acceleration, such as differences in anthropometrics (e.g., body height, mass distribution), coordination, or neuromuscular control strategies, contributed to the sex differences observed in lateral CoM displacement. Future research should investigate these additional mechanisms to fully elucidate sex-specific factors influencing balance recovery during slips.

There were no significant group differences in frontal plane trunk flexion, or in fore-aft heel slip velocity, indicating that slip severity and trunk kinematics were comparable across age groups. As such, the significant differences between older and younger adults' lateral CoM excursion were more likely due to arm abduction acceleration rather than the initial perturbation intensity. Previous work has shown that arm motion can reduce trunk velocity[22] and enhance margins of stability[40]. This present study builds on the literature by identifying arm acceleration as a key factor associated with improved balance with control of the CoM. Future studies could investigate (1) whether targeted interventions aimed at improving arm acceleration and reactive arm responses directly reduce fall risk and severity in older populations, or (2) incorporate electromyographic (EMG) spectral analyses to explore muscle activation patterns underlying differences in arm acceleration between younger and older adults. These approaches would determine if training the arms can improve functionality against a loss of balance, and help identify specific neuromuscular recruitment mechanisms, such as motor unit firing rates or muscle fiber type utilization, contributing to reactive arm movements during slips.

The results of this study should be interpreted through the lens of a number of limitations. The sample size of this study was modest with only 11 older adults and 11 younger adults analyzed, and while this study would be strengthened with analyses of additional participants, it is still informative that the frontal plane arm motion was similar to previously reported studies utilizing younger adults. Furthermore, we slipped individuals on either their left or right leg and did not factor in leg dominance in their response. Even though we did not determine leg dominance, our study is still generalizable to the population as individuals do not choose which foot to unexpectedly slip on in their natural environments (e.g. grocery stores, department stores, etc.). Additionally, our study allowed participants to wear their own shoes when stepping on a slippery surface whereas other studies standardize the shoes. This is important to consider as the shoe material, shoe treads, and the wear on the sole may affect slip severity. However, an important aspect to consider with this limitation is that people slip in the outside world wearing their own shoes in their own specific conditions. Methodologically, one potential limitation of this study was the use of a motion capture sampling frequency of 60 Hz, which may be lower than ideal for capturing rapid limb movements precisely. Although this frequency has been effectively used in prior slip perturbation research[21], future studies could utilize higher sampling rates to further validate these rapid arm acceleration measurements. Lastly, we were unable to assess arm strength as a potential contributor to arm acceleration during a slip response. Evaluating participants' strength or power would help clarify whether neuromuscular capabilities influenced the observed differences in arm acceleration and balance recovery during slip perturbations. Future research should include measures of arm strength and power to provide a more comprehensive understanding of balance control mechanisms.

Summary.

Older adults exhibit delayed and reduced arm acceleration during slips, reducing their ability to resist a loss of balance. Every 1000 degrees/$s^2$ increase in the arm acceleration response during a slip results in a 2 cm reduction in lateral center of mass displacement, highlighting rapid arm responses as a key target for reducing center of mass dynamics in aging populations.

## Methods
### Participants
A subset of 22 participants from a larger study of 56 total participants investigating the biomechanical mechanisms of slip recovery were analyzed for this study[50]. Participants were analyzed in this study if they exhibited a minimum of 10 degrees of lateral trunk flexion during the slip incident. As such, eleven community-dwelling older adults and eleven younger adults were analyzed in this IRB approved study (University of Illinois, IRB2004-0131 and IRB2004-0523) and provided written informed consent. All research was performed in accordance with the Declaration of Helsinki. Participants' anthropometrics for this study may be found in Table 2. All participants signed a written informed consent after being provided with the scope of this study. Although participants knew they would be slipped, they did not know when or how this would take place. All participants were screened by an attending physician and were excluded if they exhibited any musculoskeletal, cardiovascular or neurological conditions.

### Instrumentation
Detailed experimental methods have been previously described[50]. Briefly, all walking trials were performed on a designated walkway within the laboratory at the University of Illinois at Chicago. A 1.22 m x 2.44 m x 0.63 cm Plexiglas sheet was imbedded into the walkway. Participants walked several times across the walkway before being slipped. To induce an unexpected slip for older adults, a thin film of dried water-soluble lubricant was

quickly and quietly activated with a spray bottle of water at a time unbeknownst to the participants. Younger adults were subjected to an unexpected slip perturbation induced by stepping onto a thin applied layer of mineral oil. To ensure both groups experienced a similar slip perturbation, the static coefficient of friction remained similar between younger and older adults with a COF of $0.19 \pm 0.13$ and the dynamic coefficient of friction was approximately 90% smaller compared to the static.

Motion analysis was modeled in three dimensions with an eight-camera motion capture system collecting data at 60 Hz (Motion Analysis, Santa Rosa, CA). Reflective joint markers were carefully secured to anatomical locations that were utilized to produce a full-body 13-segment rigid body model to generate joint kinematics (OrthoTrak, Motion Analysis, Santa Rosa, CA).

All participants were fitted with a safety harness that supported the entire body weight of the participant and prevented contact of the participants' hands, knees, or buttocks with the floor if a fall were to occur. Individuals were allowed to wear their own shoes that they were comfortable with.

### Procedures

Participants were allowed to practice walking on the walkway without being attached to the safety harness to gain experience walking in an unfamiliar environment. Lighting in the laboratory was dimmed to a level where participants would not notice contaminants but bright enough to walk in the environment without needing support. The participants were aware that they may be slipped on any trial, but the participants were not aware of how many control trials would take place, nor which trial the transition of the surface from dry to wet would occur at. For the slip trial, participants were asked to turn around as a sensor needed adjustment. The sensor adjustment conducted by the researcher served as a distractor for the participant while another researcher applied the contaminant to the walkway. As such, the participants were unaware of the mechanism or trial that would induce a slip. Each participant was exposed to only one slip and the slip was randomly selected to occur on either the left or right foot.

### Data analysis

Slip onset was defined as the instantaneous moment the foot contacting the floor exhibited positive velocity (forward translation) on the slippery surface. The peak arm abduction excursion of the arm contralateral to the slipping foot was calculated[27]. Peak arm abduction acceleration of the arm contralateral to the slipping foot, and peak frontal plane trunk flexion angles were calculated. Whole-Body Center of Mass (CoM) was calculated using the mean weighted mass and position of all segments of the human body and calculated in Motion Analysis. Mediolateral CoM excursion was calculated by taking maximal lateral CoM distance away from the initial mediolateral CoM position at heel strike. Raw marker data were processed with a 2nd order, 12 Hz, low-pass butterworth filter.

### Statistical treatments

A $2 \times 2$ ANOVA (Sex [male vs. female] × Age [younger vs. older]) was conducted to examine group differences in peak arm abduction acceleration during a slip. To further assess age-related differences, one-tailed independent-samples t-tests were performed to test the hypotheses that older adults would exhibit (1) lower peak arm abduction acceleration, (2) delayed arm activation onset, (3) greater lateral center of mass (CoM) excursion, and (4) lower peak heel velocity of the slipped foot following slip initiation.

A Pearson correlation coefficient was computed to examine the relationship between peak contralateral arm abduction acceleration and lateral CoM excursion.

Finally, a multiple linear regression analysis was conducted to evaluate whether peak arm abduction acceleration, lateral trunk flexion excursion, peak heel velocity, sex and age predicted lateral CoM excursion. Predictor variables were selected based on their biomechanical relevance to reactive balance and postural control. All predictors were entered simultaneously using the enter method in SPSS. Age and sex were entered as categorical variables (younger vs. older & male vs. females), while all other predictors were treated as continuous. The significance threshold for all statistical tests was set at $\alpha = 0.05$. All analyses were performed using SPSS Statistics version 29.0 (SPSS Inc., Chicago, IL, USA).

## Data availability

The datasets generated during and analyzed during the current study are available from the corresponding author on reasonable request.

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## Author contributions
Conceptualization: JLC, KLT; Data Curation: KLT; Formal Analysis: JLC, MKL; Investigation: KLT; Methodology: KLT; Software: JLC, MKL; Visualization: JLC, MKL, KLT; Writing Original Draft: JLC; Writing Review and Editing: JLC, MKL, KLT.

## Declarations

## Competing interests
The authors declare no competing interests.

## Additional information

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