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# Exploring the role of applied force eccentricity after foot-contact in managing anterior instability among older adults during compensatory stepping responses

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ABSTRACT

*Background:* The specific mechanisms responsible for age-related decline in forward stability control remain unclear. Previous work has suggested reactive control of net ground reaction force ($GRF_{net}$) eccentricity may be responsible for age-related challenges in mediolateral stability control during the restabilisation phase of forward compensatory stepping responses.

*Research questions:* Does reactive control of $GRF_{net}$ eccentricity play a role in managing forward stability control during the restabilisation phase of a forward stepping response to external balance perturbation?

*Methods:* Healthy younger (YA) (n = 20) and older adults (OA) (n = 20) were tethered to a rigid frame, via adjustable cable. Participants were released from a standardised initial forward lean and regained their balance using a single step. Whole-body motion analysis and four force platforms were utilised for data acquisition. Forward instability was quantified as centre of mass (COM) incongruity – the difference between the first local peak and final stable anterior COM positions. The extent of $GRF_{net}$ eccentricity was quantified as the sagittal-plane angle of divergence of the line of action of the $GRF_{net}$ relative to the COM. Two discrete points during restabilisation were examined (P1 and P2), which have been suggested to be indicative of proactive and reactive COM control, respectively. Age-related differences in magnitude, timing and trial-to-trial variability of kinematic and kinetic outcome variables were analysed using two-factor ANOVAs with repeated-measures.

*Results:* OA exhibited greater COM incongruity magnitude and variability – both were reduced with trial-repetition. There were no age-related differences in the magnitude or timing of P2. Instead, OA exhibited a reduced magnitude of $GRF_{net}$ eccentricity at P1. There was a positive correlation between AP COM incongruity magnitude and P1 magnitude.

*Significance:* Different from mediolateral stability control, the present results suggest that OA may experience forward stability control challenges as a function of insufficient preparatory lower limb muscle activation prior to foot-contact.

## 1. Introduction

Fall-related injuries among Canadians over the age of 65 are a key public health concern. Although lateral falls are associated with hip fracture [1,2], the largest proportion of falls occur in the forward direction [3], with the underlying cause being an incorrect weight shift onto or between limbs [4]. Biomechanically, such control challenges may arise from inappropriately timed and scaled force output from the lower limbs during transition periods, such as during the initial response following a trip [5–7] or a restabilising step following balance perturbation [8–10]. Previous work examining mediolateral stability control during single-step balance recovery responses has revealed an association between reactive control of the frontal plane eccentricity of the net ground reaction force ($GRF_{net}$) and lateral centre of mass (COM) displacement during restabilisation, which suggests challenges controlling COM kinematics by applied forces [8,9]. The present work seeks to further understand the mechanisms responsible for age-related decline in stability control during single step balance recovery responses, by examining the reactive control of the sagittal-plane COM kinematics via the orientation of the $GRF_{net}$ during restabilisation. As challenges with single-step anterior balance recovery responses have been shown to be predictive of future falls [11], better understanding of

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the kinetic mechanisms underlying such challenges may help identify at-risk individuals and tailor fall-risk interventions.

Research examining mediolateral stability in both self-generated and perturbation-evoked stepping has revealed two important discrete time-points during restabilisation, in which the line of action of the $GRF_{net}$ acts eccentric to the COM in a manner to control whole-body angular acceleration and facilitate restabilisation [8,9]. An initial peak eccentricity (P1) occurred consistently within a 100 ms window following foot-contact – likely resulting from preparatory lower limb muscle activation prior to foot-contact – which influences stepping-limb compliance [12,13]. A second peak eccentricity (P2) occurred approximately 250 ms following foot-contact, which may be modulated reactively in response to instability during restabilisation [10,14,15]. Relative to younger adults (YA), older adults (OA) generated a similar P2 magnitude, but exhibited increased time from foot-contact to P2 [8]. This finding suggests that OA may be correctly scaling the response, but the delay could permit greater COM displacement before restabilisation. Further, the magnitude of lateral COM displacement during restabilisation was significantly correlated to the delay in the P2 eccentricity across all participants [8], suggesting the reactive control of force application may be a highly important factor regulating mediolateral stability following external balance disturbances.

The present study sought to determine if OA demonstrate evidence of increased anterior instability during restabilisation from a forward balance disturbance, relative to younger adults, by examining sagittal plane COM kinematics. Moreover, we endeavoured to understand if such increased forward instability may also be governed by reactive control of the $GRF_{net}$ orientation during restabilisation (i.e. P2 characteristics). Despite our belief that anterior instability would be brought about by changes in reactive control of force application during restabilisation, we also analysed P1 characteristics given that instability could also manifest as a function of anticipatory control mechanisms. The focus of the present work was placed on force control, via examination of the $GRF_{net}$ orientation relative to the whole-body COM, rather than force magnitude generation, as could be explored through individual $GRF_{net}$ components or external moments about the whole-body COM. While an eccentric $GRF_{net}$ orientation would restrain both linear and angular whole-body accelerations, we restricted our kinematic analysis to the forward (linear) COM component, under the premise that age-related differences in stability would be best revealed by the ability to constrain horizontal COM displacements within the support envelope rather than whole-body rotations about the COM.

We hypothesized that OA would exhibit evidence of instability during restabilisation, relative to YA, revealed by greater anterior COM displacement before restabilising. We also hypothesized that, relative to YA, OA would exhibit an increased time to generate the sagittal-plane P2 eccentricity, without age-related differences in the timing of the P1 eccentricity or the magnitudes of P1 and P2. Correspondingly, across all participants, we expected to observe a positive correlation between the timing of the P2 eccentricity and the extent of anterior COM displacement prior to restabilisation, supporting the notion that delays in $GRF_{net}$ reorientation during restabilisation may be responsible for stability control challenges.

Given the sporadic nature of instability, variability-based measures may provide information about the potential for loss of stability [8,9,16,17]. We examined the intertrial variability of COM displacements, along with the magnitudes and timings of P1 and P2 eccentricities. We also performed analyses to uncover evidence of improvements to stability control with trial-repetition. We expected to observe increases in intertrial variability of anterior COM displacement and timing of P2 among OA, relative to YA, with reductions in both magnitude and variability with trial-repetition for both age-groups.

## 2. Methods

### 2.1. Participants

Twenty community-dwelling healthy OA (age:71(5) years; mass:77.0(16.8)kg; height:1.70(0.05)m) and 20 YA (age:24(5)years; mass:68.1(10.3)kg; height:1.71(0.08)m) participated in the study. Participants self-reported no anatomical, neurological or cognitive impairments. No participant self-reported ever having experienced a previous fall; a fall was defined as an unexpected loss of balance that caused them to come to rest on the ground or floor during a normal activity of daily living. This study received ethical approval from the institutional Research Ethics Board. All participants provided informed consent.

### 2.2. Instrumentation

Synchronous kinematic ($F_s$ = 100 Hz), kinetic ($F_s$ = 2000 Hz) and electromyographic ($F_s$ = 2000 Hz) data were collected via a motion analysis system (Vicon Motion Systems, Los Angeles) and four force platforms (Advanced Mechanical Technology, Inc., Watertown). The positions and orientations of all body segments were obtained via retroreflective calibration markers and rigid clusters, as per Singer et al. [18]. Bilateral electromyographic data, from soleus and tibialis anterior, were used only for standardising the initial conditions prior to perturbation onset.

### 2.3. Protocol

Kinematic reference data for post-processing were obtained from two 60-second duration quiet standing trials performed in standardised side-by-side (McIlroy and Maki, 1997) and forward-stance configurations, which mimicked initial and final stance configurations. During experimental trials, participants were anchored to a rigid steel frame, via an adjustable cable and chest harness, in series with a force transducer. Participants adopted an initial forward lean (cable load of 10% body weight), which was monitored prior to cable release, via a force transducer mounted in series with the cable. Participants were asked to evenly distribute their weight on both legs and refrain from using their gastrocnemius/soleus to restrain their forward lean. For initial condition consistency, the interlimb weight distribution, anterior COP position, and bilateral gastrocnemius/soleus electromyographic activities were monitored to not exceed values obtained in the side-by-side stance reference trial.

Cable release occurred at pseudorandom intervals after participants had achieved the initial conditions. Participants were asked to restabilise using a single step. After restabilising, participants were to remain in the forward stance configuration for approximately 10 s, to aid in establishing the final COM position. Five of fifteen trials consisted of randomly presented catch-trials in which no perturbation was administered. Only successful single-step responses were analysed.

### 2.4. Data analysis

Kinematic data were low-pass filtered with a zero-lag, twentieth-order critically-damped filter ($F_c$ = 6 Hz). Force platform data were low-pass filtered with a zero-lag, fourth-order, Butterworth filter ($F_c$ = 50 Hz). A whole-body anthropometric model was developed using parameters from Dempster [19] and Hanavan [20] (Cited in Robertson et al. [21]) (for OA) and Zatsiorsky et al. [22] with modifications by de Leva [23] (for YA).

Restabilisation was defined as the time point after which the anteroposterior COM velocity remained within two standard deviations of the mean anteroposterior COM velocity obtained from the initial forward-stance reference trial [24]. Challenges regaining forward stability were examined using the measure of COM incongruity [24], which is

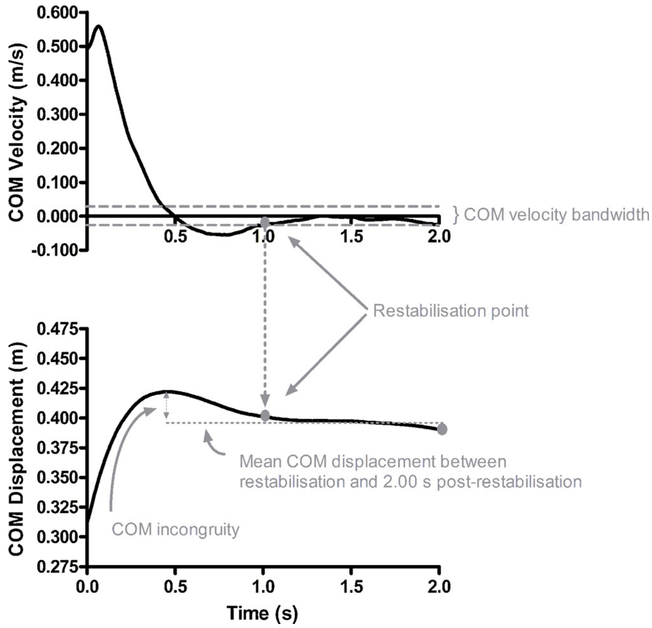


**Fig. 1.** Representative trial from one older adult participant, which conceptualizes the calculation of COM incongruity for a single trial. Top: COM velocity. Horizontal dashed lines represent the ± 2 standard deviation COM velocity bandwidth calculated from the initial forward-stance quiet standing trial. The restabilisation point (grey dot) occurs at the time when the COM velocity waveform enters and remains within this bandwidth for at least two seconds. Bottom: COM displacement, expressed relative to the initial COM position prior to perturbation onset. 1st grey dot ($t \approx 1.0$ s) signifies the restabilisation point, obtained from the COM velocity waveform; 2nd grey dot ($t \approx 2.0$ s) signifies two-seconds post-restabilisation. Horizontal dotted line signifies the mean COM displacement during the post-restabilisation interval. The difference between the mean COM displacement during the post-restabilisation interval and the local peak COM position is calculated as COM incongruity. Foot contact occurs at time = 0.

the difference between the first local maximum anterior COM position after foot-contact and the mean COM position during the first two seconds, post-restabilisation (Fig. 1).

Ground reaction forces from all force platforms were combined to yield the $GRF_{net}$ and net centre of pressure ($COP_{net}$). The angle of divergence ($\theta_d$) of the ground reaction force with respect to the COM was calculated as the difference between the sagittal-plane projection of the $GRF_{net}$ and a line joining the $COP_{net}$ and the COM. As such, $\theta_d$ quantified the eccentricity of the $GRF_{net}$ with respect to the COM. Individual angles were expressed with regard to the anteroposterior axis of the global coordinate system. Positive $\theta_d$ represents the restabilising effect of the $GRF_{net}$ (Fig. 2). As indices of the mechanisms governing whole-body balance recovery during restabilisation, analysis was focussed on two discrete time points on the $\theta_d$ waveform following foot-contact [8,9]: the first positive peak (P1) was defined as the maximum occurring within a 100 ms window following foot-contact; the second positive peak was the maximum between 100 ms following foot-contact and restabilisation.

### 2.5. Statistical analyses

COM incongruity magnitudes, P1 and P2 magnitudes and timings (relative to foot-contact) were each averaged within-subject for each block of 5 trials. The initial analysis employed separate two-factor ANOVAs with repeated-measures [between-group factor (age:2 levels); within-group factor (trial-repetition:2 levels)] for each outcome variable. Measures of effect size for the omnibus ANOVA were estimated using partial eta-squared ($\eta_p^2$), where 0.0099, 0.0588 and 0.1379 have been suggested as small, medium and large effects, respectively [25].

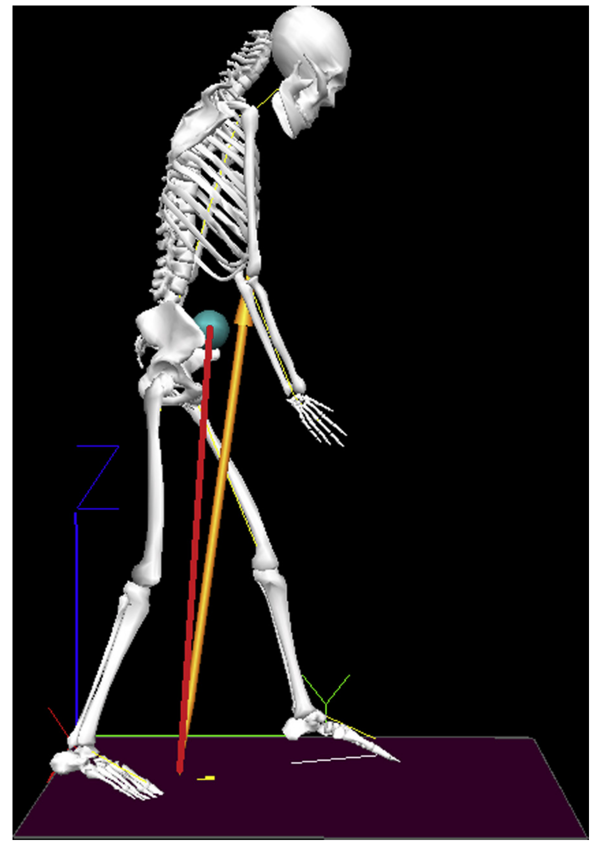

**Fig. 2.** Conceptualization of the angle of divergence ($\theta_d$) calculation; image is taken from one older adult trial at the instant of the P1 $\theta_d$. Orange arrow depicts the $GRF_{net}$ vector; red line joining the COP and COM depicts the COP-COM inclination angle. $\theta_d$ is the difference between the sagittal plane projections of the COP-COM inclination angle and the inclination angle of the $GRF_{net}$ vector, expressed relative to the anteroposterior (Y) axis of the global coordinate system. A positive $\theta_d$ value (as depicted) would represent a restabilising effect of the $GRF_{net}$ (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Interaction effects were localised with follow-up Bonferroni-corrected independent and paired-samples t-tests, as appropriate. Measures of effect size for follow-up t-tests were estimated with Cohen's d, where 0.2, 0.5 and 0.8 have been suggested as small, medium and large effects, respectively [25].

To examine the relationship between AP COM incongruity and magnitudes or timings of the P1 or P2 GRF eccentricities, Pearson product-moment correlations were performed using all participant data, using the average of 10 experimental trials for each participant.

Intertrial variability was assessed by subjecting standard deviations from each block of 5 trials to the above-described two-factor ANOVAs.

### 2.6. Secondary analyses

Despite previous work indicating age-related similarity in the temporospatial parameters of the initial response [8–10], we used the abovementioned two-factor ANOVA model to analyse temporospatial and kinematic stepping parameters from perturbation onset until foot-contact, to ensure age-related differences in stability were not brought about by factors arising prior to the onset of the restabilisation phase. The time to anteroposterior restabilisation, relative to foot-contact, was also analysed using the previously mentioned ANOVA model.

**Table 1**
Restabilisation Phase Variables*.

| | Age | | Trial Block | |
|---|---|---|---|---|
| | Younger Adults | Older Adults | 1 | 2 |
| ***Magnitude*** | | | | |
| Incongruity Magnitude (m) | 0.023 ± 0.012[aa] | 0.067 ± 0.038[bb] | 0.051 ± 0.043[aa] | 0.039 ± 0.032[bb] |
| $\theta_d$ at P1 (deg) | 2.826 ± 0.901[aa] | 1.839 ± 0.905[bb] | 2.137 ± 1.269[a] | 2.528 ± 0.986[b] |
| $\theta_d$ at P2 (deg) | 1.685 ± 0.711[a] | 1.633 ± 0.639[a] | 1.810 ± 0.764[aa] | 1.509 ± 0.703[bb] |
| Time to P1 (s) | 0.043 ± 0.008[a] | 0.042 ± 0.007[a] | 0.042 ± 0.009[a] | 0.043 ± 0.007[a] |
| Time to P2 (s) | 0.324 ± 0.056[a] | 0.362 ± 0.102[a] | 0.353 ± 0.127[a] | 0.332 ± 0.069[a] |
| ***Intertrial Variability*** | | | | |
| Incongruity Magnitude (m) | 0.014 ± 0.005[aa] | 0.036 ± 0.020[bb] | 0.031 ± 0.029[aa] | 0.019 ± 0.011[bb] |
| $\theta_d$ at P1 (deg) | 0.993 ± 0.338[a] | 0.997 ± 0.449[a] | 1.055 ± 0.617[a] | 0.934 ± 0.385[a] |
| $\theta_d$ at P2 (deg) | 0.637 ± 0.334[a] | 0.876 ± 0.817[a] | 0.998 ± 1.160[a] | 0.516 ± 0.297[b] |
| Time to P1 (s) | 0.008 ± 0.003[a] | 0.008 ± 0.004[a] | 0.009 ± 0.005[a] | 0.007 ± 0.004[b] |
| Time to P2 (s) | 0.053 ± 0.033[a] | 0.118 ± 0.111[b] | 0.112 ± 0.161[a] | 0.059 ± 0.044[b] |

* Data are presented as mean ± standard deviation. Significance values pertain only to the main effects of each omnibus ANOVA. Means with similar single superscripts do not differ significantly ($p > .05$); Means sharing dissimilar single superscripts differ significantly, $p < .05$. Means sharing dissimilar double superscripts differ significantly, $p < .01$.

## 3. Results

### 3.1. Incongruity magnitude

OA exhibited greater COM incongruity than YA, $F(1,38) = 23.68, p < 0.001, \eta_p^2 = 0.38$. Both age-groups reduced incongruity magnitude within the second trial block, relative to the first, $F(1,38) = 8.91, p = 0.005, \eta_p^2 = 0.19$.

For variability of COM incongruity, there were main effects of age, $F(1,38) = 22.48, p < 0.001, \eta_p^2 = 0.37$, and trial-repetition, $F(1,38) = 11.68, p = 0.002, \eta_p^2 = 0.24$, which were qualified by a trial-by-age interaction, $F(1,38) = 10.03, p = 0.003, \eta_p^2 = 0.21$. OA reduced the variability of COM incongruity between the first and second trial blocks, $t(19) = -3.46, p = 0.003, d = 0.94$, while YA exhibited no change. Despite this, OA continued to exhibit greater COM incongruity variability relative to YA during the second trial block, $t(38) = 3.22, p = 0.003, d = 1.02$ (Table 1).

### 3.2. P1 eccentricity

OA exhibited a reduced P1 magnitude, $F(1,38) = 11.91, p = 0.001, \eta_p^2 = 0.24$. Both age-groups increased the P1 magnitude with trial-repetition, $F(1,38) = 6.59, p = 0.014, \eta_p^2 = 0.15$. There were no main effects or interactions in the intertrial variability of P1 magnitude.

There were no main effects or interactions in P1 timing. There were no main effects of age or trial-by-age interactions in the variability of P1 timing. Both age-groups reduced the variability of P1 timing, with trial-repetition, $F(1,38) = 4.74, p = 0.036, \eta_p^2 = 0.11$ (Table 1).

### 3.3. P2 eccentricity

There was neither a main effect of age nor a trial-by-age interaction in the P2 magnitude. Both age-groups reduced the P2 magnitude during the second trial block, $F(1,38) = 9.71, p = 0.003, \eta_p^2 = 0.20$.

There were no main effects of age or trial-by-age interaction in the variability of P2 magnitude. There was a main effect of trial-repetition, as both groups exhibited reduced variability of P2 magnitude with trial-repetition, $F(1,38) = 7.30, p = 0.010, \eta_p^2 = 0.16$.

There were no main effects or interactions in P2 timing. OA exhibited increased variability in P2 timing, $F(1,38) = 6.14, p = 0.018, \eta_p^2 = 0.14$, while both groups exhibited a reduction in variability with trial-repetition, $F(1,38) = 4.85, p = 0.034, \eta_p^2 = 0.11$.

### 3.4. Relationship between COM incongruity and $GRF_{net}$ eccentricity

Pearson product-moment correlations performed on the entire sample of participants did not reveal any relationship between incongruity magnitude and either the P2 magnitude or the timings of P1 or P2. The magnitude of incongruity was significantly inversely correlated to the magnitude of the P1 eccentricity, $r(38) = -0.357, p = 0.024$.

### 3.5. Secondary analyses

There were no age-related differences in step-length, swing-time or in forward COM position or velocity at foot-contact. OA exhibited a significantly longer time to restabilisation than did YA, $F(1,38) = 3.67, p = 0.027, \eta_p^2 = 0.12$ (Table 2).

## 4. Discussion

The present work sought to better understand the biomechanical mechanisms responsible for age-related decline in forward stability control by examining the control of the $GRF_{net}$ orientation, which regulates COM kinematics. While OA exhibited greater COM incongruity and variability of incongruity, which were both reduced with trial-repetition, we found no age-related differences in the magnitude or timing of the P2 eccentricity. Instead, OA exhibited a reduced magnitude of $GRF_{net}$ eccentricity at P1. Both groups increased the magnitude of P1, decreased the magnitude of P2, and reduced the intertrial variability of the timing of both P1 and P2 with trial-repetition. Interestingly, there was an inverse correlation between the extent of AP COM incongruity and the P1 magnitude. Different from ML stability control, the present results suggest that preparatory lower limb muscle

**Table 2**
Secondary Analyses*.

| | Age | |
|---|---|---|
| | Younger Adults | Older Adults |
| **Swing Phase** | | |
| Step Length (m) | 0.512 ± 0.085[a] | 0.505 ± 0.076[a] |
| Swing Time (s) | 0.185 ± 0.038[a] | 0.174 ± 0.029[a] |
| AP COM Position at Foot Contact (m) | 0.381 ± 0.053[a] | 0.373 ± 0.047[a] |
| AP COM Velocity at Foot Contact (m/s) | 0.594 ± 0.130[a] | 0.544 ± 0.085[a] |
| Time to AP Restabilisation (s) | 2.20 ± 0.480[a] | 2.63 ± 0.677[b] |

* Data are presented as mean ± standard deviation. Means with similar single superscripts do not differ significantly ($p > .05$); Means sharing dissimilar superscripts differ significantly, $p < .05$.

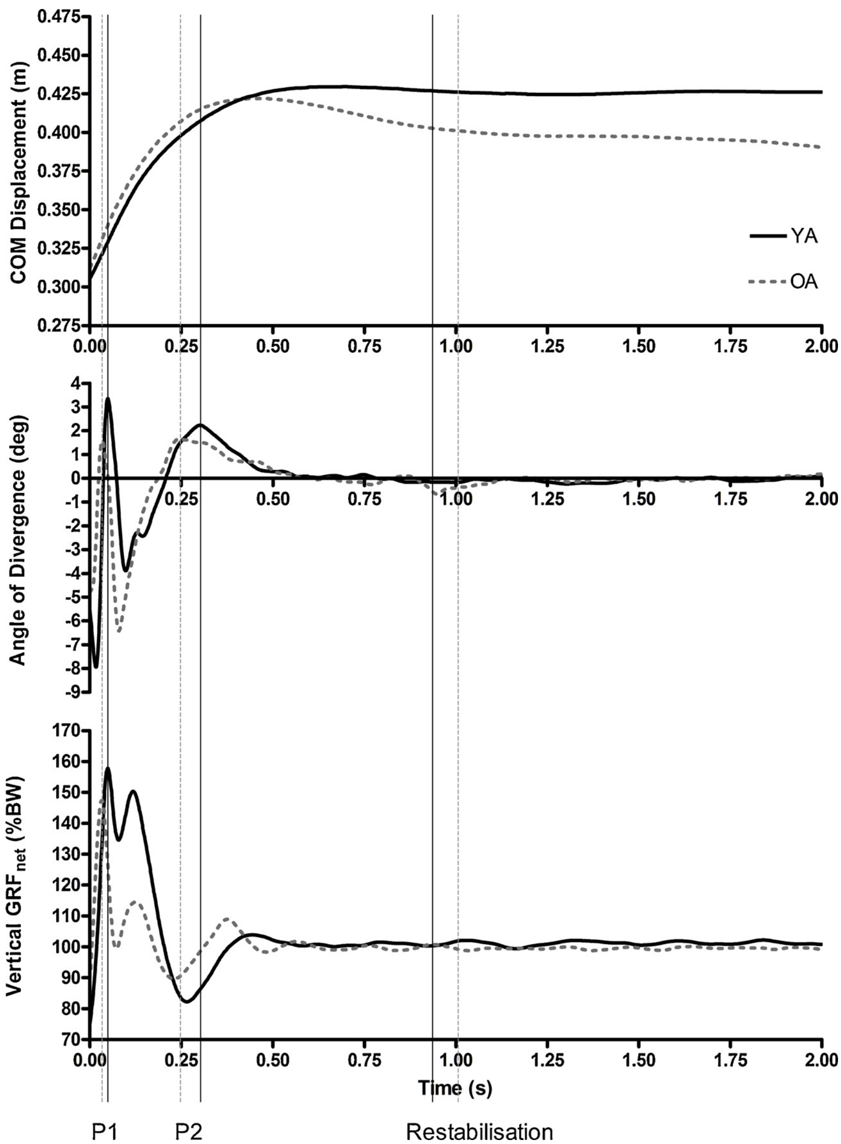


**Fig. 3.** Representative trial from one older adult (OA – grey dashed) and one younger adult (YA – black solid) participant. Top: centre of mass displacement time series during restabilisation, expressed relative to the initial COM position, prior to perturbation. Centre: Angle of divergence ($\theta_d$) of the net ground reaction force ($GRF_{net}$) relative to the centre of mass (COM). Positive values signify a $GRF_{net}$ orientation tending to cause restabilising whole-body angular acceleration; negative values signify a $GRF_{net}$ orientation tending to cause destabilising whole-body angular acceleration. Zero values indicate a centric $GRF_{net}$ line of action. Bottom: Vertical component of the $GRF_{net}$, expressed as a percentage of body weight (%BW). Solid black (YA) and dashed grey (OA) vertical lines depict P1 and P2 events during the restabilisation phase, along with the point of restabilisation. Foot contact occurs at time = 0.

activation prior to foot-contact may be an important mechanism to regulate AP restabilisation during stepping responses.

Similar to our previous work on ML instability [8,9,18], the present results support the idea that increased COM incongruity during the restabilisation phase may be a marker of stability control challenges. Increased AP COM incongruity among OA would place the COM closer to the anterior stability limits and may signify challenges with the underlying control of COM kinematics. In conjunction with the age-related increase in intertrial variability of COM incongruity, OA may experience an increased probability for a given restabilisation response to fail to constrain the COM during the initial step [26,27]. Given the sporadic nature of instability and falls, parallel measures of COM incongruity magnitude and variability may have the potential for use as metrics to reveal an individual's fall-risk. Future prospective work, however, will be necessary to reveal an association between the present indices of instability and falls [16].

Consistent with previous work [8,10,14,28,29], the absence of age-related differences in the initial temporospatial and kinematic parameters of the stepping response, prior to the restabilisation phase, suggest the challenges in stability control among OA are unlikely the result of either the rapidity of the initial movement or step-placement. Rather, the present age-related differences in the P1 eccentricity magnitude along with the correlation between P1 magnitude and the extent of AP COM incongruity suggest that AP instability among OA may arise from challenges with the control of applied forces immediately following foot-contact. Although the P1 divergence manifests after foot-contact, the underlying lower limb extensor muscle forces were likely initiated prior to foot-contact, during terminal swing-phase [12,13], which influence stepping-limb compliance on foot-contact. This is given support by the average timing of the P1 divergence (Table 1) – too brief to be modulated by sensory information upon foot-contact – and that the P1 divergence would be increased by a larger peak vertical $GRF_{net}$ component (Fig. 3). As such, the observed challenges in generating the P1 divergence could either be a consequence of age-related alterations in the planned response to the perturbation or in the generation of sufficient lower limb force output, as described below.

The planned response to the perturbation may have been inappropriate among OA if the destabilising effect of the forward lean angle prior to perturbation onset, the AP velocity following the perturbation, or the necessary restabilising vertical force magnitude on foot-contact was misjudged. Age-related loss of plantar tactile sensitivity [30] or challenges with sensory integration [31] could lead to difficulties estimating the forthcoming perturbation magnitude from the initial forward lean angle. Age-related somatosensory challenges may also heighten the reliance on visual or vestibular information to detect whole-body motion after perturbation onset [32]. Inaccurate somatosensory information used to estimate the amplitude of the perturbation [33], may dictate an improper level of muscle activation and limb compliance on foot-contact, resulting in the observed reduction in P1 magnitude and increased AP COM incongruity among OA. Nevertheless, age-related error in proactive control, as a function of sensory input, cannot completely account for the observed increase in AP COM incongruity and reduction in P1 magnitude among OA, as this would likely lead to incorrect estimates, rather than systematic underestimates, of the perturbation magnitude or muscle force required to restabilise.

Age-related deficits in lower limb force output [34] have been associated with balance control challenges [35] and could be proposed as an additional explanation to specifically account for the increased AP COM incongruity and reduced P1 magnitude among OA. The P1 divergence is contingent on the ratio between horizontal and vertical $GRF_{net}$ components, along with the COM and COP locations. As we found no age-related alterations in step-length, swing-time, AP COM position or velocity at foot-contact, it may be possible that the reduction in P1 magnitude among OA is related to regulation of individual horizontal and vertical $GRF_{net}$ components upon foot-contact. Consistent with previous work noting age-related reductions in the initial deceleration peak in the vertical GRF during gait [36], the most likely possibility is that OA may be experiencing difficulty generating a sufficient vertical $GRF_{net}$ component (Fig. 3) at P1, which limits $GRF_{net}$ eccentricity. Similarly, age-related increases in the posteriorly-directed horizontal $GRF_{net}$ component immediately after foot-contact could also account for the reduction in P1 magnitude. This, however, may be less likely as braking forces are typically coupled with increased COM velocity or increased step length; neither was observed in the present work.

All participants reduced AP COM incongruity magnitude and variability with trial-repetition. These kinematic modifications occurred alongside trial-to-trial increases in P1 magnitude, reductions in P1 timing variability and reductions in the P2 magnitude and variability. Given the association between AP COM incongruity and P1 magnitude, it is possible that reductions in AP COM incongruity were, in part, a result of the increased P1 magnitude occurring with trial-repetition. If P2 is indeed a reactive response to instability occurring after foot-contact [8,9], reductions in P2 magnitude and variability with trial-repetition may signify an improved planned response to the perturbation, reducing the need to reactively manage instability after foot-contact. Perturbation-based training programs appear to reduce falls risk among OA [37] and OA have been found to improve the restabilisation response during the period from perturbation onset until foot-contact [27]. The present results provide additional insight into the mechanisms underlying such practice-related improvements, as OA may improve the kinetic response by tuning preparatory muscle activation to improve stability after foot-contact.

Despite such improvements in stability control with trial-repetition, age-related differences persisted. Correspondingly, age-related challenges in AP stability control following balance perturbation are likely a function of both stability control- and force-related factors. If initial group differences in stability were solely a function of age-related thresholds in lower limb force production, OA would be incapable of making improvements with trial-repetition – it is highly probable that corrections in proactive control are needed. Similarly, as age-related differences in stability persist after trial-repetition, it is equally probable that decrements in lower limb force generation are also responsible.

In summary, our findings coincide with previous work [8,9] suggesting the control of applied force eccentricity during restabilisation to have important links to stability following external perturbation. Different from the reactive control of ML stability [8,9], AP stability may be regulated proactively, prior to foot contact, by dictating stepping-limb compliance during the initial response. OA may face difficulties regulating GRF eccentricity, and hence regaining AP stability, as a result of either challenges detecting initial perturbation magnitude or generating sufficient lower-limb extensor intersegmental moments. Further work is necessary to separate these factors.

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