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Age differences in the control of postural stability during reaching tasks

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ABSTRACT

Reaching tasks are commonly performed during daily activities and require anticipatory postural adjustments (APAs) to ensure a stable posture during movement execution. Age-related changes in APAs may impact dynamic balance and cause postural instability during reaching tasks made from standing. The present study examined age differences in postural control during reaching to targets located at different heights. Fourteen young adults (aged 20.0 ± 1.5 yrs) and 16 community-dwelling older adults (aged 73.4 ± 5.3 yrs) participated in the study. The task involved reaching forward to grasp a cylinder, and returning to an upright position as fast and accurately as possible. Postural control was analyzed using the center of pressure (COP) during four phases of the task: COP displacement during APA production, COP trajectory smoothness during the reach and return phases, and COP path length during the recovery phase following movement. APA amplitude measured by COP displacement and COP path length during the recovery phase was larger in older compared to young adults. Dynamic balance represented by COP trajectory smoothness was reduced with age. In both age groups, APA amplitude was largest and COP trajectory smoothness the least during low target reaches.

The results demonstrate that, while older adults can alter APAs in order to maintain postural stability, control of COP during movement execution, particularly during low target reaches, is compromised with aging. These findings have clinical implications for both the assessment of dynamic balance and the development of balance training programs.

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1. Introduction

Reaching tasks are an important component of daily activities and require the control of the arms and trunk, particularly when reaching from a standing position. Reaching movements disturb postural stability due to the production of joint reaction torque and changes in posture. To counteract these perturbations and maintain dynamic balance during movement execution, anticipatory postural adjustments (APA) are generated prior to movement onset [1]. APA also create necessary momentums to initiate movements toward the reach target [2]. Lastly, APA keep the center of mass within the stability limits and contribute to a stable postural transition from one body configuration to another [2].

Postural stability is essential for functional independence in older adults. Impaired postural control is a major risk factor of falls [3], leading to heightened morbidity and mortality [4]. The need to control postural disturbances arising from moving multiple body segments can be challenging for older adults, where up to 95% of daily activities involve both the arms and trunk movement [5]. In older women, approximately 17% of falls occur during reaching or leaning [6]. Despite the high frequency of reaching tasks in everyday activities, the factors impacting postural stability during reaching in older populations remain to be identified.

APA are programmed in a feedforward manner, with APA duration and amplitude scaled to the estimated perturbations associated with the forthcoming movement [7,8]. APA duration and amplitude increase with increases in reaching movement speeds [8] and distances [9]. The mechanism for producing APA may be altered with age [10,11]. During arm raising movements performed from a standing position, APA amplitudes are comparable between young and older adults [11]. In contrast, older adults have shortened APA durations [11] and more frequently recruit postural muscles later relative to the onset of prime mover muscles compared to young adults [10]. While inadequately programmed APA in older adults may cause postural instability during

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movement execution, this view has only been confirmed during leg movements where both APA and dynamic balance after movement onset were examined [12].

In addition to changes in APA, aging is associated with declines in dynamic balance as reflected by reduced stability limits, *i.e.* the maximum range of center of pressure (COP) displacement within the base of support (BOS) [13]. In older adults, the demand to maintain dynamic balance during reaching may vary depending on the reach direction. While 20% of older adults report difficulties when reaching overhead, over 50% have difficulties during downward-directed movements, such as stooping [14]. Upward reaches are associated with greater age-related reductions in maximum COP displacement than reaching forward [15]. In addition, older adults have lower balance confidence when reaching on tiptoes compared to reaching at eye-level [15]. Taken together, these findings suggest that age differences in dynamic balance can be influenced by the reach direction.

Dynamic balance during standing reach is commonly examined by maximum COP displacement, a simple, two-point measure of COP trajectory [13,15]. In contrast, the spatial-temporal characteristics of the COP trajectory have been primarily analyzed in quiet stance only [16]. In upper limb studies, movement smoothness, based on the time derivative of acceleration (jerk), is indicative of coordinated motor performance [17,18]. This measure has been used to quantify arm movement coordination in the elderly [17,19] and in stroke [20]. In lower limb studies, jerk scores have been used to distinguish differences in stride smoothness in athletes [21] and to quantify smoothness of COP trajectories associated with impaired postural control during gait initiation in Parkinson's disease [22]. Thus, jerk-based measures provide a sensitive means of detecting and quantifying changes in coordination during a variety of movements, including tasks requiring dynamic postural control.

In many studies examining dynamic balance, individuals were required to hold the end reaching posture while keeping the COP close to the boundaries of the BOS [10,11,15]. In everyday reaching activities, the task often is not to reach and hold, but involves reaching forward, grasping, and returning to an upright position. Postural control during such returning movements that shift the COP backward has not been investigated in older adults. Moreover, with age-related changes in APA [10,11], perturbations associated with movement execution may remain uncompensated [11]. Whether postural stabilization at the end of a movement is affected by age is unclear.

The purpose of this study was to identify age differences in postural control during reaching tasks that involve reaching forward to grasp targets at various heights, and then returning to an upright position. It was hypothesized that older adults would show reductions in APA, dynamic balance, and postural stability at the end of movement compared to young adults.

2. Methods

2.1. Participants

Fourteen young adults (20.0 ± 1.5 years) and 16 community-dwelling older adults aged 65 years and over (73.4 ± 5.3 years) were recruited from the local community. Participants were right-handed, able to walk independently, had intact lower-limb sensation and normal or corrected vision. All were in good health with no history of diabetes or other neurologic conditions, and with body mass index ≤ 30. All procedures were approved by the University of Michigan Institutional Review Board. Participants gave their consent prior to data collection.

2.2. Procedures

Participants stood barefoot with their heels separated by a distance of 10% of body height. Foot positioning remained the same throughout all trials. The target was a cylinder (5 cm diameter, 15 cm high, 300 g) placed at 110% of arm's length in front of the right shoulder. Grasp location was indicated by a yellow band, 2.5 cm wide. Three target heights were used: high (top of the head), medium (shoulder height), and low (knee level).

Participants reached and grasped the cylinder using their right dominant arm, and returned to an upright position while holding the target. Participants initiated the task at a self-chosen time following a verbal "Go" signal and completed the task as fast as accurately as possible. Participants were required to keep their feet in place during the task. For each target height condition, 3 trials were collected consecutively while target height order was randomized. Participants rested for 1 min after completing each condition.

2.3. Data collection

A motion capture system (MotionSTAR, Ascension Technology, Burlington, VT) recorded 3D kinematics of the reaching arm with a sensor placed on the radial styloid. A force platform (AccuSway, AMTI, Watertown, MA, USA) recorded ground reaction forces and moments, and was zeroed after every trial and every rest break to prevent drift. The signals from the force plate were filtered by a built-in, primary 200 Hz low-pass, two-pole filter. Balance Clinic software (AMTI, Watertown, MA, USA) calculated COP data. All kinematic and force plate data were collected simultaneously at 100 Hz.

2.4. Data processing

Arm movement and COP data were processed using custom-written programs (Matlab Version 6.0, MathWorks, Natick, MA) and a zero-lag, 4th order Butterworth filter using a 6 Hz cutoff. A 5% peak velocity threshold was used to identify onsets and offsets of arm movements and COP displacement in the anteroposterior direction (COP-AP). Center of pressure variables were analyzed during the APA, reach, return, and recovery phases (Fig. 1).

2.4.1. Anticipatory postural adjustments variables

The APA duration was measured from COP-AP displacement onset to the onset of the reaching movement. The amount of COP-AP displacement prior to the onset of reaching movement represented the APA amplitude.

2.4.2. Dynamic balance variables

Dynamic balance during reach and return arm movements was quantified using a normalized jerk score [17]:

$$\text{Normalized jerk score} = \sqrt{\left(\frac{1}{2} \times \int \frac{J2(t)dt \times d5}{l2}\right)}$$

where J is the third derivative of COP displacement in the anteroposterior (COP-AP) and mediolateral (COP-ML) directions, d is the duration of each phase analyzed, and l is the path length of COP-AP and COP-ML displacement. Smaller normalized jerk scores indicate smoother and coordinated movements [17,18].

The cumulative COP displacement in the AP and ML directions was used to calculate COP path length during the recovery phase. This phase corresponded to the 2 s period immediately following maximum backward COP displacement.

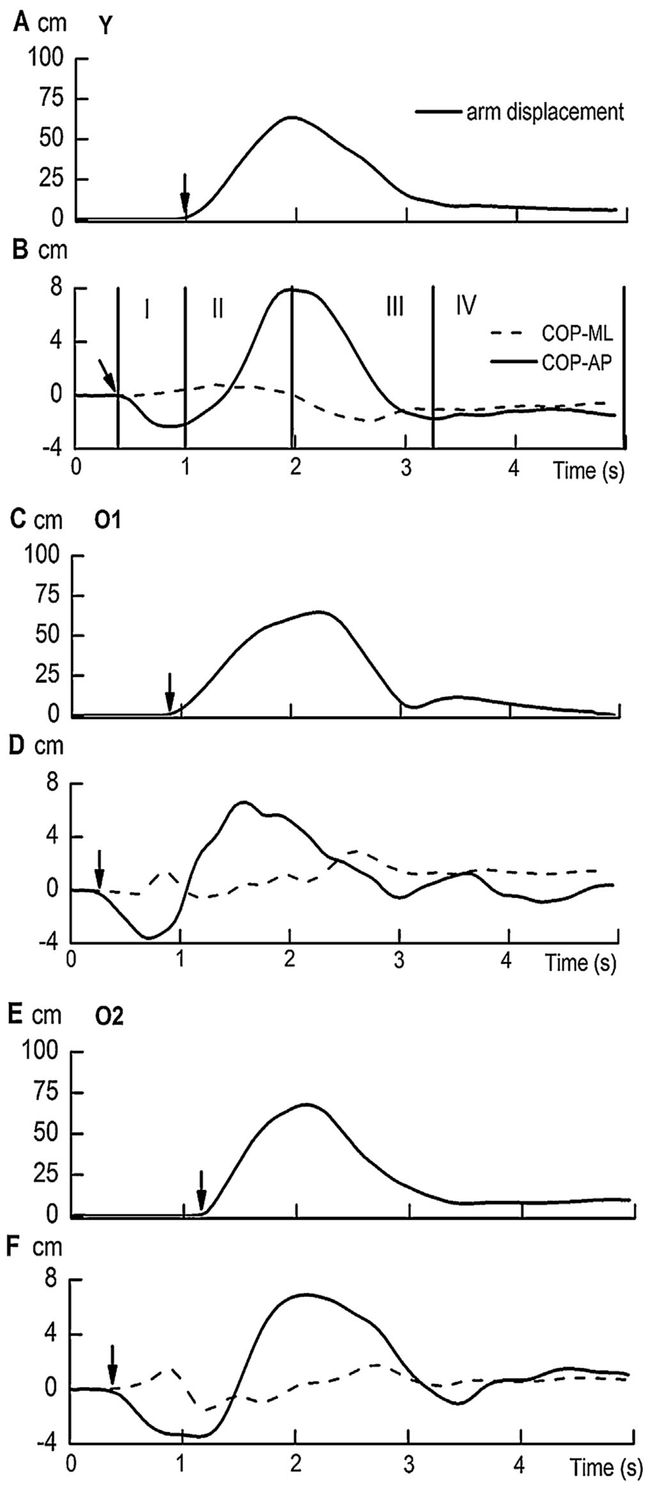

Fig. 1. Averaged arm displacement during a forward reach and return movement made by a young (A – Y1) and two older (C – O1, E – O2) adults. The corresponding center of pressure (COP) recorded in the mediolateral (COP-ML) and anteroposterior (COP-AP) directions is also shown (B, D, and F). I–IV represent the four phases of the task. Phase I: anticipatory postural adjustments (APA) – the period from the onset of COP-AP displacement to the onset of reaching movement, Phase II: reaching – the period from the onset of reaching movement to the time of maximum COP-AP forward displacement, Phase III: return – the period from the time of maximum COP-AP forward displacement to the offset of COP-AP backward displacement determined using a threshold of 5% peak COP-AP velocity, Phase IV: recovery – the 2-s period following the offset of COP-AP backward displacement. Arrows indicated the onset of arm movement and COP-AP displacement.

2.5. Statistical analysis

Statistical analysis was performed using the IBM-SPSS Statistics Version 19 (IBM-SPSS, Armonk, NY). Preliminary analysis using a Linear Mixed Model revealed no significant effect due to trial number. Therefore, for a given condition, averaged data were analyzed using a General Linear Model, with group as between subject factor and target height as within subject factor. Tukey's LSD was used for *post hoc* analysis of interaction effects. The significance level was $p < 0.05$.

3. Results

3.1. Arm movements

Young and older adults performed the task at comparable peak arm movement speeds during the reach and the return phases. Mean reach movement speeds were significantly faster when reaching to high (young: 212 ± 13 cm/s, older: 216 ± 11 cm/s) compared to low targets (young: 174 ± 11 cm/s, older: 172 ± 10 cm/s) ($p < 0.001$). Similarly, return movements were performed faster for high (young: 256 ± 15 cm/s, older: 260 ± 9 cm/s) compared to low (young: 178 ± 14 cm/s, older: 161 ± 8 cm/s) targets ($p < 0.001$).

3.2. Anticipatory postural adjustments

The COP moved primarily in the anteroposterior direction, with the initial COP displacement directed backwards (Fig. 1B, D and F). Regardless of target height, APA amplitude was significantly larger in older than in young adults ($p < 0.05$) (Fig. 2A) while APA duration was comparable in both groups (Fig. 2B). In both groups, APA amplitude and duration were affected by target height, with low target reaches associated with the largest APA amplitude and longest APA duration ($p < 0.001$) (Fig. 2A and B). APA, however, were not different during reaches made to medium and high targets.

3.3. Dynamic balance

Maximum forward COP displacement as a percentage of foot length did not differ significantly between age groups for a given target height (high – young: 32.1 ± 1.5%, older: 31.6 ± 1.8%; medium – young: 22.5 ± 1.8%, older: 21.4 ± 2.2%; low – young: 25.3 ± 1.9%, older: 23.9 ± 1.4%). Maximum COP displacement in the AP direction occurred approximately at the end of the reach movement. As shown in Fig. 3, time of maximum COP displacement across all target heights was highly correlated with the end of the reach movement in both young and older groups.

COP trajectory smoothness was reduced in older adults. Jerk scores were significantly larger in older than young adults during the reach and the return phases ($p < 0.01$) (Fig. 4). During the reach phase, an age-related decline in COP trajectory smoothness was most noticeable during reaches made to low targets where jerk scores were almost 60% greater in older compared to young adults (Fig. 4A). During the return phase, COP trajectories were less smooth regardless of target height as reflected by jerk scores that were 55 – 70% greater in older compared to young adults (Fig. 4B). For both groups, jerk scores were largest during reaching to low targets and smallest during medium target reaches ($p < 0.01$) (Fig. 4A). In contrast, target heights did not influence COP trajectory smoothness during the return phase in either group (Fig. 4B).

3.4. Postural stabilization during recovery

Altered COP trajectory formation seen during the return phase in older adults persisted during the transition to an upright

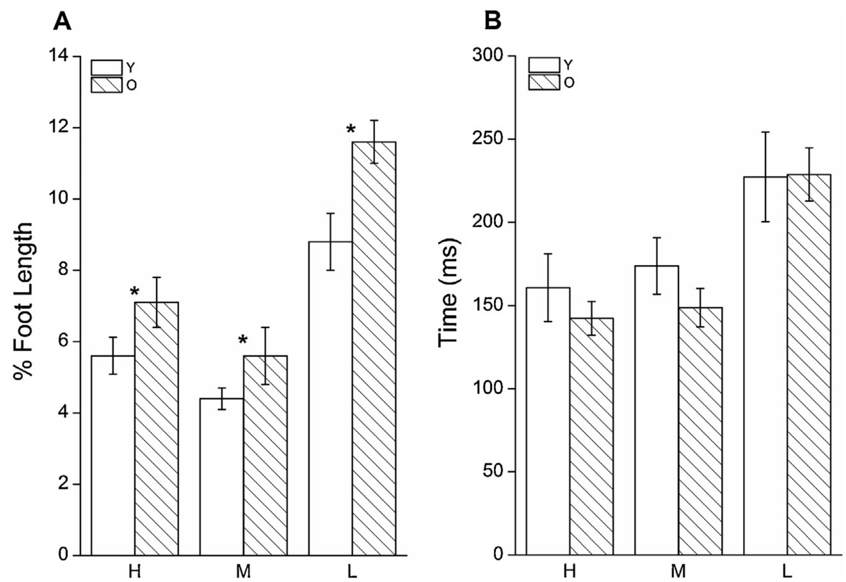

Fig. 2. A. Mean (±1SE) APA amplitude obtained from COP displacement in the AP direction (COP-AP) in young (Y) and older (O) adults. COP data expressed as a percentage of foot length for H (high), M (medium), and L (low) targets. Asterisks indicate significant group differences $p < .05$. B. Mean (±1SE) APA duration for young and older adults for each reach height. Abbreviations as in Fig. 1.

position. COP path length measured over a 2 s period during the recovery phase was larger in older than young adults at both low and medium height targets ($p < 0.01$) (Fig. 5). No significant group differences were observed following recovery from high target reaches.

4. Discussion

Using a standing reach paradigm, this study examined age differences in APA, dynamic balance during movement execution, and postural stabilization at the end of movement. The reaching task resembled everyday activities that involve reach-to-grasp movements toward objects of different heights. Current results did not support the hypothesis based on previous findings [10,11] that aging is associated with reductions in APA amplitude and duration. APA amplitude represented by COP displacement was larger in

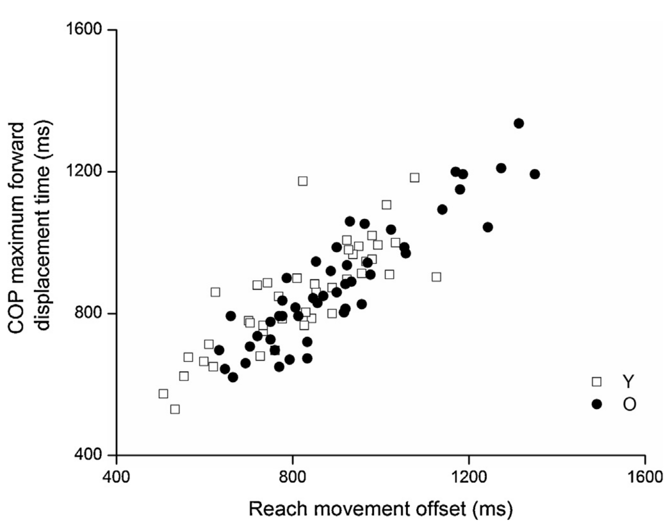

Fig. 3. A. Relationship between reach movement offset and time of COP-AP maximum forward displacement in young (Y – open symbols) and older (O – filled symbols) adults. Data were averaged across trials within a subject for each target height condition.

older compared to young adults while no differences in APA duration were found between age groups, regardless of target heights. As hypothesized, older adults had poorer dynamic balance measured by COP trajectory smoothness during both the reach and return phases. In addition, COP path length during the recovery phase was larger in older than young adults, suggesting an age-related decline in the ability to stabilize posture at the end of a self-initiated movement. The effect of target height suggests that reaching to low targets presents the greatest challenge to postural control than reaching to medium height or high targets, particularly for older adults.

APA amplitude and duration increase with increasing distance [9] and speed of arm movements. Since both groups performed the reach movement at comparable speeds and distances, larger APA amplitudes observed in older adults were not produced in anticipation of faster or larger reach movements. Older adults may have utilized an alternative APA programming strategy [23]. During forward reaching, a larger backward COP displacement can increase the momentum arm, *i.e.* the distance between the COP and the center of gravity, in order to produce forward angular momentums to move the body toward the reach target [24]. With age, however, the same amount of backward COP displacement has been found to produce less forward momentum during the APA phase associated with forward oriented movements such as gait initiation [23]. In this regard, older adults in this study may have increased the APA amplitudes in an attempt to generate sufficient momentum for producing the forward reach movement.

Alternatively, older adults may have adopted a different movement strategy that requires larger forward momentum and hence, larger COP displacements during the APA phase. Larger APA amplitude in older adults may reflect an active control strategy to increase the safety margin for preventing a loss of balance. Postural stability emerges from the interaction between active forces by muscles, passive effects from reaction and gravitational forces, and other external forces from the environment [1]. When postural perturbations are predictable, the presence of APA is associated with smaller compensatory postural responses induced by the perturbation [25]. In the present study, older adults may have increased APA amplitude to minimize the impact of passive and external forces, which are less predictable and can

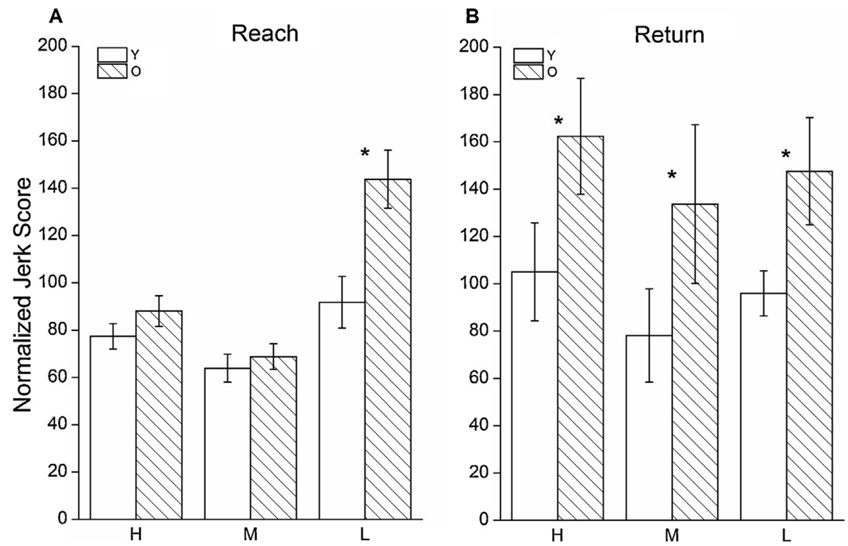

Fig. 4. A. Mean (±1SE) normalized integrated jerk (NIJ) scores as a measure of COP trajectory smoothness during the reach (II) phase (*$p < .01$). B. Mean (±1SE) jerk scores during the return (III) phase (*$p < .05$). Abbreviations as in Fig. 2.

destabilize posture. Therefore, larger APA amplitude in older adults may serve to compensate for age-related declines in postural control systems [16].

This study is the first to report an age-related reduction in COP trajectory smoothness during movements performed from a standing position. These changes can be considered to reflect reduced postural control occurring throughout the execution of dynamic tasks involving both trunk and upper limb movements. The present findings extend previous reports of reduced COP trajectory smoothness during gait initiation in individuals with impaired postural control [26]. Thus, measures of COP trajectory smoothness may provide a more sensitive means of quantifying dynamic postural control beyond conventional measures of maximum COP displacement [13].

Target heights had a significant impact on APA and dynamic balance. For both young and older adults, APA amplitude and duration were greatest at low targets, reflecting a higher need for postural stabilization prior to movement onset. While target height affected preparatory adjustments similarly in both age groups, low targets presented a greater challenge to older adults during the dynamic components of the task. Specifically, older but not young adults exhibited decreased COP smoothness and increased COP path length during the recovery phase when reaching to low targets. This may reflect a higher demand for dynamic postural stabilization in older populations during movements requiring greater arm-trunk coordination [27].

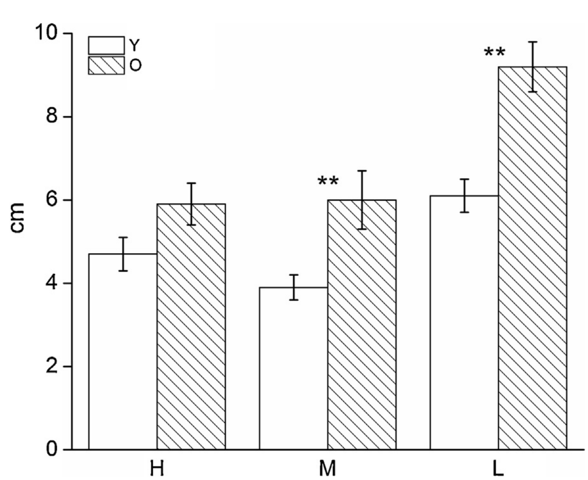

Fig. 5. Mean (±1SE) COP path length in both the COP-AP and COP-ML directions during the recovery phase (IV) for each target height (H – high, M – medium, L – low).

During the return phase, older adults experienced difficulty in smoothly shifting the COP backward. Muscle synergies moving the COP backward primarily consists of dorsal muscles, such as gastrocnemius and biceps femoris [28]. Since ankle plantarflexion torque is reduced in older adults [29], it is possible that aging may affect dorsal muscle strength to a greater extent. In addition, the anatomy of the ankle and foot provides a larger foot area to move the body forward but restricts backward-oriented movements. These musculoskeletal and biomechanical factors can limit the ability of older adults to smoothly control the COP trajectory in the backward direction.

Aging not only impacts APA production and dynamic balance, but also affects the process of regaining stability at the end of a movement. Upon returning to an upright posture, older adults are less able to stabilize the COP position over a 2 s period as measured by COP path length. In quiet stance, longer COP path length has been reported to be associated with a history of falls in older adults [16]. Difficulty in stabilizing the COP position after a forward reach has also been found in patients with type 2 diabetes [30]. With altered APA and dynamic balance control, older adults may not be able to compensate for postural disturbances arising from movement execution and remain unstable as they transition from a dynamic movement state to a static posture.

5. Conclusion

Aging may be associated with larger APA amplitudes and indicative of the increased postural stabilization prior to movement onset. Older adults have reduced dynamic balance as represented by a decrease in COP trajectory smoothness during movement execution, and encounter greater difficulty in stabilizing the COP at the end of the movement. Further studies are necessary to investigate whether the programming of APA can be improved after balance training and whether these changes are associated with better postural stability during and after movement execution. The results of this study underscore the clinical importance of incorporating reaching movements to different heights, particularly lower heights, when assessing balance and designing balance training programs. Lastly, COP trajectory smoothness quantified by jerk scores can be used as an indicator of dynamic balance during movement execution.

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Conflict of interest statement

The authors of this manuscript declare that there is no conflict of interest.

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