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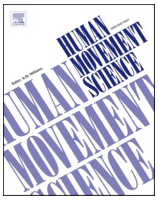

Keeping balance during head-free smooth pursuit: The role of aging

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ABSTRACT

Standing balance is often more unstable when visually pursuing a moving target than when fixating on a stationary one. These effects are common in both young and older adults when the head is restrained during visual task performance. The present study focused on the role of head motion on standing balance during smooth pursuit as a function of age. Three predictions were tested: a) standing balance is compromised to a greater extent in older than young adults by gaze target pursuit compared to fixation, b) older adults pursue a moving target with greater and more variable head rotation than young adults, and c) greater and more variable head rotation during the smooth pursuit task is associated with greater Center of Pressure (CoP) sway. Twenty-two (22) older (age: 71.7 ± 8.1, 12 M / 10 F) and twenty-three (23) young adults (age: 23.6 ± 2.5, 12 M / 11 F) stood on a force plate while either fixating a stationary or smoothly pursuing a horizontally moving target (31.9° peak-to-peak visual angle). CoP (Bertec Balance Plate), head kinematics (Vicon Motion Analysis) and head-unconstrained gaze (Pupil Labs Invisible) were synchronously recorded. The root means square (RMS) of CoP velocity increased during smooth pursuit compared to fixation regardless of age ($p < .05$), while the interquartile CoP range increased only in older and not in young participants ($p < .05$). We also calculated the head rotation range (peak to peak cycle amplitude) of motion and variability (SD of range of motion) across the cycles of the smooth pursuit task. Older adults pursued the moving target employing more variable ($p = .022$) head yaw rotation than young participants although the mean range of head rotation was similar between groups ($p =. 077$). The amplitude and variability of head yaw rotation did not correlate with CoP sway measures. Results suggest that head-free pursuing of a moving target decreased balance to a greater extent in old than young individuals when compared to fixation. Nevertheless, postural sway during head-free smooth pursuit was not associated with the extent or variability of head rotation.

1. Introduction

Balance control is crucial for the maintenance of autonomous function and mobility in old age. Older adults show increased reliance

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on visual input for balance control to compensate for their age-related decline in muscle proprioception and somatosensation (Eikema, Hatzitaki, Konstantakos, & Papaxanthis, 2013). At the same time, the majority of falls in older adults occur during a postural transition (sit to stand, stand to walk transitions) or weight transfer (Robinovitch et al., 2010), actions that require a rapid re-orientation of the gaze from the current to the next spatial location. When re-orienting their gaze while standing or walking on a treadmill, older adults exhibit greater head rotation compared to young adults (Cinelli, Patla, & Stuart, 2008; Hirasaki, Kubo, Nozawa, Matano, & Matsunaga, 1993). This is accompanied by the concurrent shoulder and hip rotations to the intended direction of motion pointing to an en-bloc balance strategy, which could compromise stability. Moreover, in real-world conditions such as walking down a hallway with free gaze or fixating on an earth-fixed object while walking, older adults employ fewer, smaller, and slower saccadic eye movements (Dowiasch, Marx, Einhäuser, & Bremmer, 2015) which could negatively affect visual perception and early motion processing required for successful balance control.

Gaze shifts while keeping upright stance can affect body balance. There is some evidence that pursuing a target moving along 11° of amplitude can reduce postural sway in young healthy adults (Rodrigues et al., 2015). However, the majority of the studies suggest that smooth pursuit of targets moving along small amplitudes (~6°) typically compromises standing balance relative to fixating on a stationary one (Guerraz & Bronstein, 2008; Thomas et al., 2017; Thomas, Bampouras, Donovan, & Dewhurst, 2016). This effect on balance control does not seem to be age-specific, because young and older adults increased mediolateral Center of Pressure (CoP) sway to a similar extent during smooth pursuit compared to fixation of a stationary target (Thomas et al., 2016). Similarly, walking into a room while fixating or smooth pursuing another person decreased balance control compared to free gaze, but again, this effect was similar in young and older females (Thomas, Donovan, Dewhurst, & Bampouras, 2018). Most previous studies either verbally instructed their participants to keep the head stable during visual task performance or selected a small target eccentricity ($<15^{o}$) that could be achieved by isolated eye movements (Glasauer, Schneider, Jahn, Strupp, & Brandt, 2005; Stoffregen, 2006; Thomas et al., 2016; Thomas et al., 2017). In the real world however, accurate vision is mostly achieved through coordinated eye and head movements (Kowler, 2011), which can produce larger gaze excursions, extending the initial visual field restrictions (Freedman & Sparks, 1997).

Head rotations during gaze shifts can have important implications on posture, especially in aging. Visual functions are reported to decline with aging, as visual acuity gets poorer (Maruta, Spielman, Rajashekar, & Ghajar, 2017) and eye movements become hypometric and slower (Maruta et al., 2017; Paige, 1994; Zackon & Sharpe, 1987). By engaging the head to achieve a desired gaze shift, one can obtain additional extra-retinal information about spatial orientation and self-motion perception from head-neck proprioception (Pettorossi & Schieppati, 2014). These additional signals can increase certainty about gaze orientation (Sağlam, Lehnen, & Glasauer, 2011) and so they could possibly compensate for age-related visual decline. This might be the reason that older adults seem to engage their head more strongly when shifting their gaze, at least when using saccades (Cinelli et al., 2008; Hirasaki et al., 1993). Nevetherless, smaller head rotations have been observed in older adults during locomotion as well (Paquette, Paquet, & Fung, 2006). Despite these discrepancies, a rising concern is whether additional head rotations during gaze shifts can influence posture. For instance, inertial torques generated by rather large head rotations during daily activities that require visual search could challenge standing balance by increasing postural sway and therefore also the risk of falling, especially in aging. Indeed, large (~65°) head rotations during gaze re-orientation while walking appear to disturb body balance in young, but not in older adults (Paquette et al., 2006). However, in this study, older adults appeared to rotate their head to a lesser extent ($\sim 40^{o}$). As rather small head rotations have a smaller mechanical impact on posture, the additional sensory input that they provide from head-neck proprioception leading to more reliable estimates spatial perception and body orientation (Pettorossi & Schieppati, 2014), could have beneficial effects on posture. Surprisingly, however, it is not known how such head rotations could affect standing balance, especially in aging. We are here interested in examining how pursuing a slowly moving target impacts older adults' standing balance when the head is free to move within a relatively limited range (≅ 32° range of motion) imposed by the target's eccentricity. In the literature, we found only one study investigating age effects on smooth gaze pursuit when the head is free during standing (Paquette & Fung, 2011), which showed an age-related decline in tracking accuracy and gaze-target coupling but did not report any effects on standing balance.

The present study was designed to address the above issues focusing on the following aims: a) investigate the effect of head-free smooth pursuit (relative to the control fixation task) on older and young adults' standing balance, b) identify smooth pursuit strategies of young and older adults based on the amplitude and variability of head yaw rotation, and c) assess the relationship between head motion and standing balance. Static balance was assessed during a head-free gaze fixation on a stationary target and during the smooth pursuit of a target moving horizontally on a stationary (black) background. Three predictions were made: a) standing balance is compromised to a greater extent in older than younger adults by the smooth pursuit when compared to the gaze fixation task, b) older adults pursue the moving target with greater and more variable head yaw rotation, and c) the greater age-induced sway is related to greater and more variable head yaw rotation for pursuing the moving target.

2. Materials and methods

2.1. Participants

Twenty-two (22) older (age: 71.7 ± 8.1, 12 M / 10 F) and twenty-three (23) young (age: 23.6 ± 2.5, 12 M / 11 F) adults participated in the study. Young participants were volunteers among university students, whereas older participants were recruited from daycare community centers for older adults. Inclusion criteria were: (1) no symptoms suggestive of eye disorder that could affect the reliability of the gaze measurement; (2) no orthopedic diagnoses preventing standing; (3) no medications known to affect the nervous system or balance. Participants were assessed with the Mini-Mental State Examination and for visual acuity using a Snellen board. Younger and older participants achieved a score ≥ 24 and ≥ 20/100 respectively, both considered acceptable for inclusion in the study. Participants were informed about the purpose and the experimental protocol of the study and gave written informed consent. Experimental procedures were approved by Aristotle University of Thessaloniki Ethics Committee on Human Research in accordance with the Declaration of Helsinki (Approval number 100/2022).

2.2. Apparatus, visual stimuli, and task protocol

A force platform (Balance Plate 6501, Bertec, USA, sampling rate: 100 Hz) recorded the vertical ground reaction force and moments in the anteroposterior (AP) and mediolateral (ML) direction to calculate the Center of Pressure displacement (CoP). A TV screen (LG 60LA620S-ZA, 60 in., 1.5 m horizontal x 0.8 m vertical; screen refresh rate: 60 Hz) was positioned 1.95 m in front of the participant, centered at eye level. Kinematic data were captured using a 10-camera system (Vicon Motion Systems, Oxford, UK, sampling rate: 100 Hz). Reflective markers were attached at the following anatomical landmarks: a) head (two markers on the forehead), b) right and left acromion processes, c) right and left trochanter. The Vicon's Software Development Kit (SDK) was used to establish communication between the Vicon system software (Nexus v. 1.8.5) and LabView (version 8.6, National Instruments Corporation, 2008) (Bitter, Mohiuddin, & Nawrocki, 2006), allowing the visual stimuli presentation and synchronous sampling and digitization of the force, marker kinematics and target motion signals via the Vicon's data acquisition board (MX Giganet). The Pupil Invisible mobile eye tracking system (Pupil Labs GmbH; sampling rate: 200 Hz) was used to capture the gaze parameters. The synchronization of the Vicon motion analysis and the visual tracking systems was based on the synchronous recording of a sound that was generated by the LabView custom software developed to control the experiment. The sound was stored as an analog signal in both Nexus and the eye-tracking software and used to synchronize the time series offline.

The visual stimulus was a red circular (disk-shaped) target (diameter equivalent to 1.46° of visual angle) projected onto a stationary black background, which occupied the full-screen dimensions (Fig. 1). The vertical center of the TV monitor was adjusted to the participant's eye level. The target was always presented 10% below the vertical center of the screen to correspond with the mean standard line of sight and could be stationary (fixation task) or move horizontally covering 90% of the screen's width (visual angle of 31.9°) at a constant velocity of 15.96°/s (smooth pursuit task). Because head rotation does not commonly get involved in gaze shifts of <15° (Hallet, 1986), the target's range of motion (31.9°) was chosen to encourage the participants to engage their heads while smoothly pursuing the visual target. The target's motion signal was a sine wave created in LabView, with a frequency of 0.25 Hz that gave 15 cycles of horizontal motion in 60 s.

Participants stood in a bipedal upright position at the center of the force platform, barefooted with feet parallel, keeping inter-malleolar distance to 10% of the shoulder-to-shoulder distance and with arms free hanging on body sides (Fig. 1). While standing, they

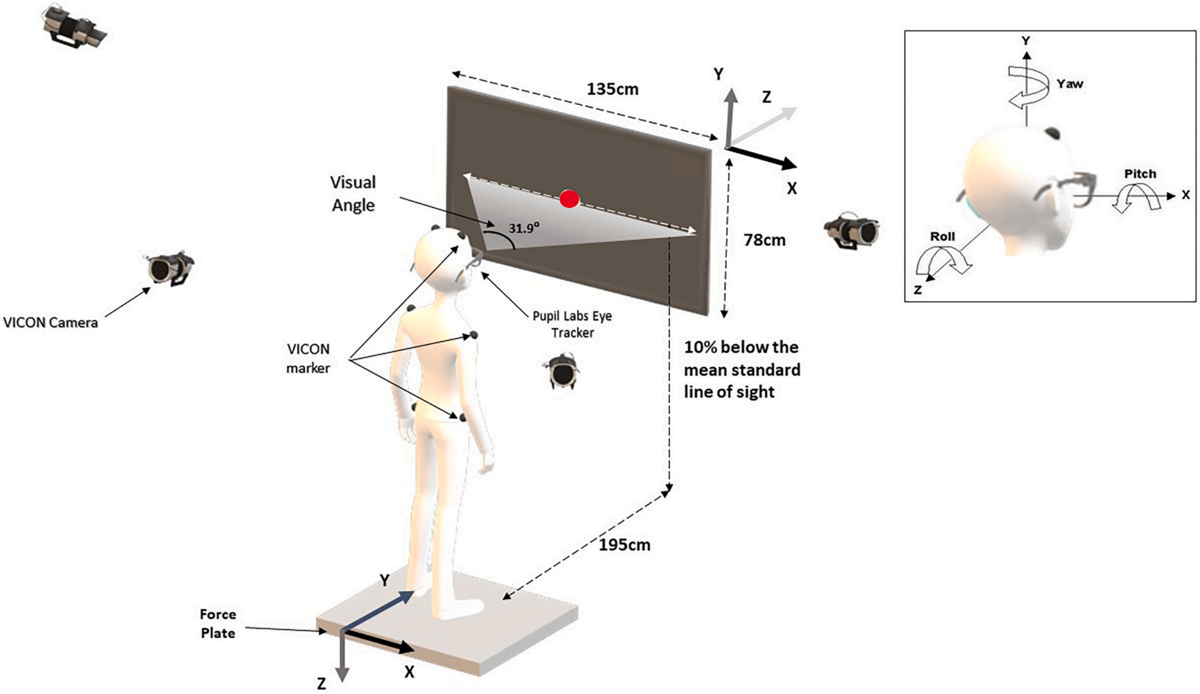

Fig. 1. Experimental setup and task. The participant stood on a force platform in front of a TV monitor and fixated a red circular target displayed on a black background (fixation task, 30s) or pursued the horizontal motion of the target (smooth pursuit task, 60s). Ground reaction forces, gaze and head kinematics were synchronously recorded. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

were asked to perform one of the following visual tasks in a randomized order: a) fixate the stationary target for 30″ (fixation task), b) pursue the horizontally moving target for 60″ (gaze pursuit task). The reason for a rather short recording during fixation was to avoid having our participants get distracted during this task. In contrast, for the pursuit task, we were interested in obtaining as representative data as possible, and therefore we recorded longer trials. No instruction about head stabilization was given. Instead, participants were free to move body segments at their convenience to accurately fixate on or pursue the visual target. The two conditions were part of a larger study protocol.

2.3. Data analysis

Force, kinematic, and gaze time-series were processed in MATLAB (MATLAB, 2019) using custom-made scripts. For the data analysis, the first and last 5 s of each (fixation and pursuit) trial were disregarded to avoid signal irregularities due to the transient effects of task familiarization and fatigue (Thomas et al., 2016). As mentioned earlier, the fixation task was recorded for 30 s whereas the pursuit task was for 60 s. Therefore, to allow for the most representative comparisons between fixation and pursuit tasks, and only for such comparisons, we used the first 20 s of the fixation task and the first 20 s of the pursuit task (after subtracting the first 5 s of each trial).

2.3.1. CoP

The ML and AP CoP time-series were first computed from the vertical ground reaction force vector and the two moments. The CoP time-series were then filtered with a 4th-order low-pass Butterworth filter (cut-off frequency 5 Hz) and differentiated to calculate CoP velocity. CoP sway was summarized with the following dependent variables: i) interquartile CoP range in the AP and ML direction (CoP range), and ii) Root Mean Square of the CoP velocity (RMS CoP velocity) in the AP and ML direction.

2.3.2. Head kinematics

For the calculation of head rotation in the yaw plane, the Cartesian 2D linear position coordinates (x,y) of the right and left head markers were smoothened with a digital low pass Butterworth filter (cut-off 5 Hz) and then converted to angular coordinates using the arc tangent function (Winter, 2009). The head range of motion (only for the smooth pursuit task) was calculated for each target cycle and then this value was averaged across the 13 cycles of target motion (after subtracting the first and last cycle of the trial) to get a) the mean and b) the standard deviation (SD) of the head rotation amplitude as measures of the amplitude and variability of head rotation, respectively.

2.3.3. Gaze

To calculate the two-dimensional linear coordinates of the gaze position on the monitor, Apriltag markers were placed at the 4 corners of the TV screen. Next, using an algorithm for recognizing their position, the active registration surface was calibrated (Olson, 2011). The calculation of the points on the screen where the two eyes' lines of sight converged, was performed through the Pupil Labs Player software. The initial recording of the gaze position on the TV surface was calibrated to pixels before it was converted into a visual angle in degrees.

For the smooth pursuit task, the spatial coupling between the gaze and the target motion was assessed as the peak of the cross-correlation function (CCF) between the gaze and the target motion time-series. A value of 1 represents the perfect spatial coupling between the time-series.

2.3.4. Sample size estimation and statistical analysis

Given the limited studies on the topic and the absence of information about effect size of previously published work on the effect of head-free pursuit on standing balance, the sample size was estimated a priori (Kirk, 1982) based on the empirically expected age-induced difference in RMS of CoP velocity during the smooth pursuit task. After collecting pilot data on 5 young and 5 older participants in this task condition, we considered a mean expected age group difference of 0.3336 cm ± 0.3231 (SD) with $\alpha = 0.05$ and power $= 0.90$. Using this information, we calculated that a minimum of 21 participants per group (effect size $= 1.032$) would be sufficient to test our hypothesis about the effect of age on body balance (Power Analysis, SPSS, v.27).

Prior to statistical testing, all variable distributions were checked for normality (Kolomogorov-Smirnov test) and homogeneity of variance (Levene's test) across age groups. To test the 1st hypothesis of the study, the effect of age group and visual task (fixation vs. smooth pursuit) on the CoP sway variables (CoP range and RMS of CoP velocity) was investigated employing 4 seperate 2 × 2 ANOVAs, one for each CoP variable, with repeated measures on task. Estimates of effect size on all dependent measures are reported using partial η^2. Task-by-group interactions were tested by pairwise comparisons between the visual tasks performed separately for each group. Analysis testing the 1st hypothesis was conducted by using the datasets of the first 5–25 s of each task (fixation and smooth pursuit). For testing the 2nd and 3rd hypotheses, which were concerned only with the smooth pursuit task, larger time-windows of 5–55 s were used to include more data that can allow a more representative analysis of the participant's behavior. To test the 2nd hypothesis of the study associated with age-related differences in the smooth pursuit strategy, the mean and SD of head yaw rotation amplitude, as well as the peak of the gaze-target CCF were compared across age groups employing *t*-test or non-parametric Mann-Whitney *U* test for independent samples. To test the 3rd hypothesis of the study, Pearson's correlations were calculated between the CoP sway variables and the head yaw rotation variables during the smooth pursuit task, separately for the young and old group adults.

3. Results

3.1. Fixation vs gaze pursuit effects on standing balance

All postural variables were normally (Kolomogorov-Smirnov test: $p > .05$) and homogeneously (Levene's test $p > .05$) distributed. Fig. 2 shows exemplar ML-AP CoP traces of one older and one younger participant, separately for the two visual tasks.

Pursuing the moving target increased the *CoP interquartile range* in the AP direction [F (1,43) =14.29, $p < .001$, $\eta 2 = 0.250$; Fig. 3a] relative to fixation but not in the ML direction [F (1,43) = 0.010, $p =. 921$, $\eta 2 = 000$; Fig. 3b]. More importantly, there was a significant age group by task interaction on CoP range in both the AP [F (1,43) = 5.03, $p = .030$, $\eta 2 = 0.105$; Fig. 3a] and the ML direction [F (1,43) = 4.59, $p = .038$, $\eta 2 = 0.097$; Fig. 3b]. Subsequent post hoc pairwise comparisons confirmed that older adults increased the CoP interquartile range in the AP direction when pursuing the moving target compared to fixating it [(t (21) = 3.56, $p = .002$] but not in the ML direction ($p > .05$). By contrast, young participants did not change the CoP interquartile range in either direction (both $t < 1.39$, both $p > .05$). Overall, there was no main effect of age group on the CoP interquartile range, neither along the AP nor along the ML direction (both $F < 2.19$, both $p > .146$, both $\eta 2 < 0.049$).

The destabilizing effect of the target pursuing task on *the RMS of CoP velocity* was common across age groups as confirmed by a main effect of the task [AP direction: F (1,43) =16.09, $p < .001$, $\eta 2 = 0.272$, Fig. 3c; ML direction: F(1,43) = 18.56, $p < .001$, $\eta 2 = 0.301$, Fig. 3d] and by the absence of a significant group by task interaction effect ($p > .05$). The RMS of CoP velocity in the ML direction was larger in older than younger adults [F (1,43) =18.68, $p < .001$, $\eta 2 = 0.303$; Fig. 3d), but it was similar across age groups in the AP direction ($p > .05$; Fig. 3c).

3.2. Age-related differences in head rotation

The range of the head yaw rotation during the fixation task was $<1^{o}$ for all group participants regardless of age, which suggests that the head was stationary during the fixation task.

Fig. 4a and b show the individual head yaw rotation time series during the smooth pursuit task for the old and young group participants, respectively, plotted together with the group mean (thick black line). Individual values of the mean head rotation

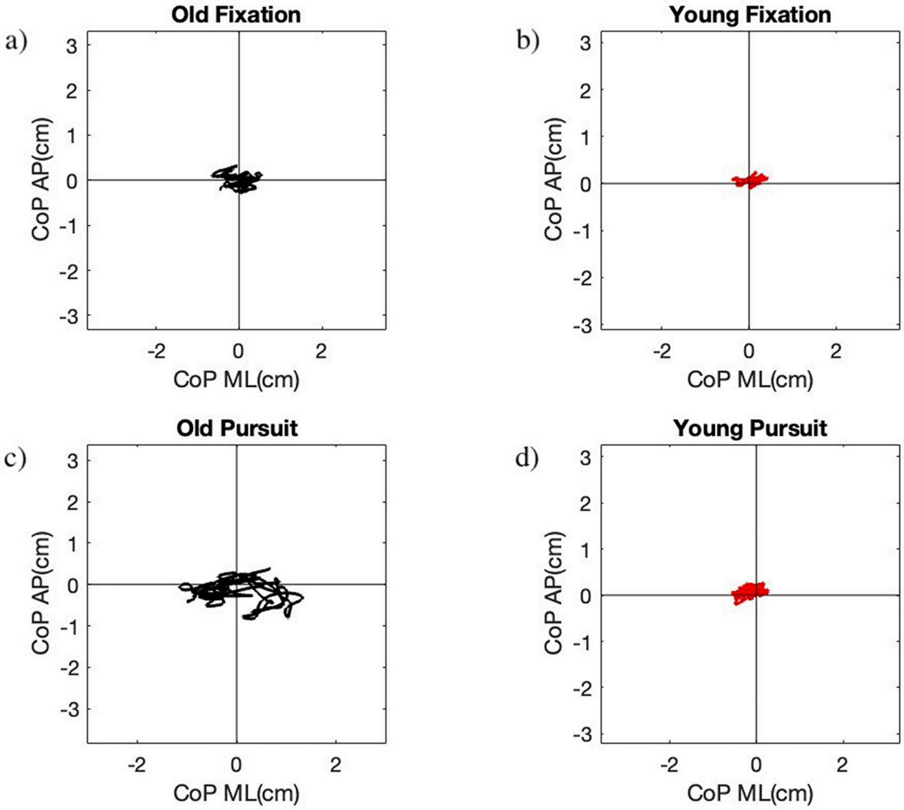

Fig. 2. Representative Centre of Pressure (CoP) displacement plotted in the mediolateral (ML) vs the anteroposterior (AP) direction during the fixation (a,b) and the smooth pursuit (c,d) task of one old (a,c in black) and one young (b,d in red) participant. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

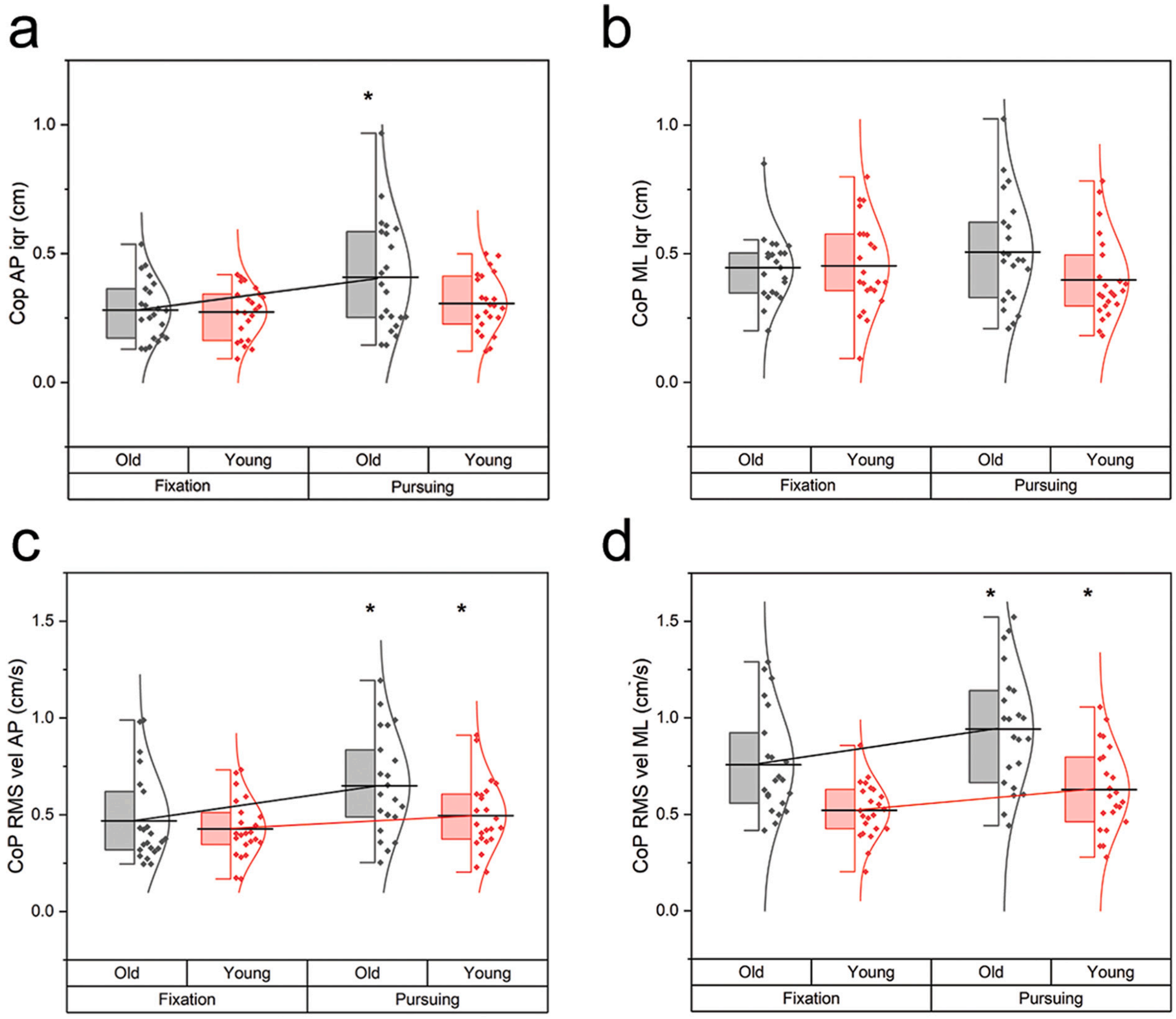

Fig. 3. Interquartile CoP range (CoP iqr, cm) in the anteroposterior (a) and mediolateral direction (b), and root mean square (RMS) of CoP velocity in the respective directions (c,d). Individual values along with group means (horizontal line) and distribution curves are shown for fixation vs pursuit in the old (black) and young (red) group *: > than fixation ($p < .05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

amplitude (Fig. 4c) were widely spread, positively skewed (skewness old group: 1.267, young group: 1.617), not normally (Kolomogorov-Smirnov test: young group: $p = .002$, old group: $p = .038$) and non-homogeneously distributed (Levene's test $p < .05$). For this reason, non-parametric comparisons for independent samples (Mann-Whitney U test) were used to compare differences across age groups. Analysis suggested that the mean of head yaw rotation amplitude for pursuing the moving target was not different between age groups (Mann-Whitney U = 175.0, $p = .077$, Fig. 4c).

The SD of the head rotation amplitude across the smooth pursuit cycles (Fig. 4d) was normally distributed but only in the old group (Kolomogorov-Smirnov test: old group: $p > .05$, young group: $p = .004$). SD of head amplitude was also homogeneously distributed across groups ($p > .05$). Non-parametric between-group comparison confirmed a significantly larger inter-cycle SD of head rotation amplitude for the old than the young group participants (Mann-Whitney U = 152.0, $p = .022$).

The gaze-target peak CCF during the smooth pursuit task did not reveal a significant effect of age (Mann-Whitney U = 146.0 $p > .05$). All participants showed gaze-target peak CCF values >0.8 (>80%).

3.3. Relationship between head rotation in smooth pursuit and CoP sway

To further investigate the possible relationship between head rotation during smooth pursuit and standing balance, we correlated both the inter-cycle mean amplitude and the SD of head yaw rotation with postural measures obtained during the smooth pursuit task. Please note that, for this analysis, we consider CoP and head rotation across the complete 50 s long duration of the trials. The

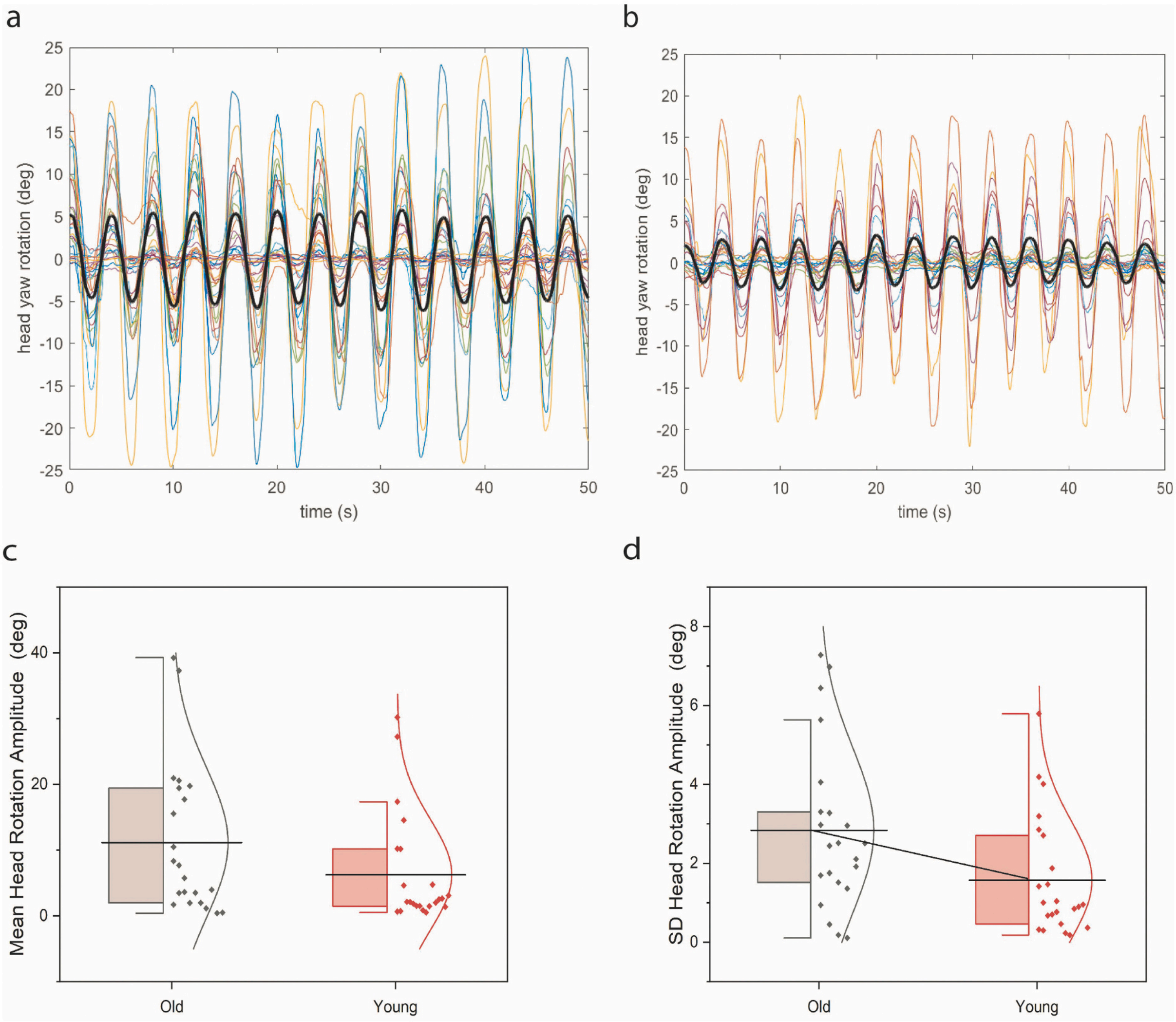

Fig. 4. Individual head yaw rotation time series plotted along the group mean (black line) for the old (a) and the young (b) group during the 13 cycles of smooth pursuit. Mean (c) and standard deviation (d) of head rotation amplitude across the 13 cycles of the smooth pursuit task. Individual values along with group means (horizontal line) and distribution curves are shown for the old (black) and young (red) group. *: > in Old than Young group ($p < .05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

scatterplots with the linear regression fit between the mean amplitude and SD of head yaw rotation and each of the CoP sway variables are plotted in Fig. 5 separately for the old and young group participants. These scatterplots revealed non-significant relationships between head rotation and sway measures, with *r* values ranging from −0.23 to 0.33 ($p > .05$).

4. Discussion

The results of the present study confirmed our 1st hypothesis suggesting that head-free smooth pursuit of the horizontally moving target increases the CoP amplitude (range) of older, but not of younger, adults relative to gaze fixation. However, despite the more variable head rotation of the older participants in the pursuit task, there was no association between the amplitude and variability of head rotation and CoP sway measures. Thus, the third hypothesis attributing the age-related greater sway to head yaw movements employed by older adults during the smooth pursuit task was not confirmed.

4.1. The effect of the visual task on standing balance

CoP sway velocity in the AP and ML direction increased during the head-free smooth pursuit compared to the fixation task and this effect was similar across age groups. The present results are in contrast with previous studies that suggested reduced postural sway in young adults during smooth pursuit compared to fixation (Rodrigues et al., 2015). On the other hand, they are in line with other work

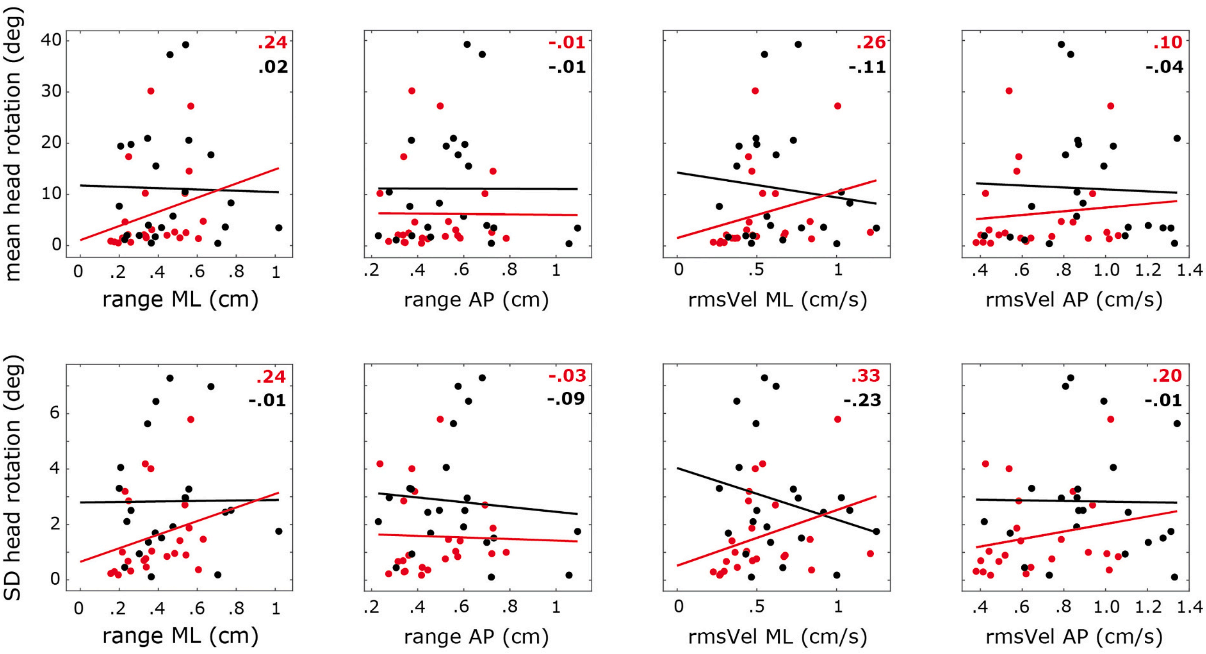

Fig. 5. Scatterplots with linear regression lines between mean amplitude (first row) and SD (second row) of head yaw rotation and postural sway variables (CoP interquartile range and RMS CoP velocity in the ML and AP direction) for the old (black) and young (red) group. Correlation coefficients (shown on the right top corner of each panel) were low and non-significant. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

showing that the smooth pursuit of a target moving on a static visual field destabilizes both the static (Laurens et al., 2010; Thomas et al., 2016) and dynamic balance (Thomas et al., 2017) relative to gaze fixation. The increased CoP velocity noted during the smooth pursuit task in both age groups could be due to the retinal slip induced by the eye movement, for instance, while following the moving target's image focused on the fovea. Preserving the stability of a given visual input on the retina is important for the accurate detection of postural shifts (Schulmann, Godfrey, & Fisher, 1987). However, during the smooth pursuit, even though the target is centralized on the fovea, the background retinal flow is shifting in the opposite direction to the target's motion and is thus more difficult to integrate for the postural control (Glasauer et al., 2005). Extraretinal signals, such as eye proprioception and efference copy of the eye movement, are thought to improve balance by improving the detection of body sway, but these are effective only for larger lateral body sway (for a review see Guerraz & Bronstein, 2008). Smooth pursuits that complicate these signals could possibly be detrimental to postural control.

In addition to the age-independent increase of RMS of CoP velocity, the present results revealed an age-specific increase of the CoP interquartile range during the smooth pursuit relative to the fixation task. Contrary to previous studies that restricted head motion during visual task performance by selecting a small target eccentricity ($<15^{\circ}$ of visual angle) (Stoffregen, 2006), the present experimental paradigm imposed a relatively larger visual angle of the target motion ($\cong 31^{\circ}$) which required a relatively small head rotation during the smooth pursuit task. This revealed an age group by task interaction on CoP interquartile range in both the AP and ML direction indicating that CoP amplitude increased to a greater extent in older than young participants during head-free smooth pursuit, in contrast to the previously reported absence of age-related differences on the postural sway increase between fixation and smooth pursuit (Thomas et al., 2016). It is possible that our head-free pursuing task necessitated greater head rotation in older adults to ensure gaze stability and greater sensorimotor certainty (Sağlam et al., 2011). Such an additional head rotation could increase CoP sway due to the inertial effects associated with the head's movement. Yet, when rotating the head, additional sensory input from neck muscles and vestibular end organs can provide a more reliable estimate of the body in space and therefore improve body posture (Pettorossi & Schieppati, 2014). To further explore these possibilities, we compared the mean amplitude and variability of head yaw rotation during the head-free pursuit task across the two age groups and investigated its possible impact on standing balance.

4.2. Age-related differences in head rotation and gaze strategy during smooth pursuit

Older adults pursued the horizontally moving target with more variable head rotation than younger adults did. Generally, older adults appear to engage their heads during visuomotor task performance more than younger adults do during vertical and horizontal saccades performed from a semi-tandem posture (Polastri et al., 2019) but also when re-orienting gaze during walking (Cinelli et al., 2008; Hirasaki et al., 1993), though this is not always the case (e.g., Paquette et al., 2006). The additional head engagement could be a compensation for age-induced limitations of the aging visual system, as this is reflected, for instance, in poorer positional precision

(Kolarik, Margrain, Freeman, & a., 2010; Maruta et al., 2017), range (Moschner & Baloh, 1994; Paige, 1994), and eye-target velocity gain during smooth pursuit tasks (Kanayama et al., 1994; Lee, Ji Kim, Shin, Hwang, & Han Lim, 2019; Matheron, Yang, Lê, & Kapoula, 2008; Moschner & Baloh, 1994). Head rotation can allow for smaller and slower eye movements and decrease uncertainty about gaze orientation (Sağlam et al., 2011) improving visuomotor accuracy. This idea is in line with the present results revealing a high cross-correlation between gaze and target motion (CCF > 0.8) regardless of age. Considering that the target was often followed with a head rotation that, on average, accounted for ~33% of the target's range of motion, it could be argued that head rotation contributes to gaze orientation by providing extra sensory input, in line with previous postulations (Sağlam et al., 2011). Previous work also confirms the absence of age-related deficits in visuomotor accuracy when the head is free to move during gaze pursuit tasks performed in a natural environment (Dowiasch et al., 2015) or during visuo-postural coordination tasks that require tracking of periodically moving targets with the whole body (Sotirakis, Kyvelidou, Mademli, Stergiou, & Hatzitaki, 2016; Sotirakis, Kyvelidou, Stergiou, & Hatzitaki, 2017). Yet, this high correlation may result from the fact that the target motion was temporally and spatially predictable, which allowed participants to anticipate the impending target motion and predict the target's spatial continuation based on previous experience, a skill that is preserved in old age (Chapman, Hollands, & a., 2007; Sprenger et al., 2011).

4.3. The impact of head rotation on standing balance

Based on the findings so far, one might have expected that the more variable head rotation of older adults is associated with the greater age-related CoP range observed during the smooth pursuit task compared to fixation. Contrary to this expectation, analyses did not reveal an association between head rotation and any of the CoP sway measures during the head-free smooth pursuit task. Correlation coefficients were low, ranging from -0.23 to 0.33, and non-significant (Fig. 5). The flat regression lines, for most of the sway measures, indicate that those, mostly older, participants who engaged their head motion to pursue the moving target did not exhibit increased CoP sway. Therefore, the more variable head movement does not seem to be the reason for the increased CoP range noted in the smooth pursuit task compared to fixation and thus appears not to hamper balance control. This might be related to the fact that target motion was relatively slow ($\cong 15^{o}$/s) compared to previous studies ($> 20^{o}$/s; e.g., Paquette & Fung, 2011; Maruta et al., 2017), and so the induced head rotation during the smooth pursuit task in our study might have been relatively slow, minimizing inertial influences that could compromise postural stability.

5. Conclusions

Our study reveals, for the first time, that when the head is unrestrained during the performance of visual tasks, gaze smooth pursuit of a horizontally moving target increases CoP sway to a greater extent in older than young individuals. We hypothesized that this may be due to an age-specific gaze strategy of engaging greater and more variable head yaw rotation in target pursuit. This hypothesis was not confirmed by the present results which did not demonstrate an association between head rotation amplitude and variability during target smooth pursuit and CoP sway measures neither in younger nor in older adults. This suggests that posture is robust against the more variable head rotation engaged by older adults when smoothly pursuing a moving target. Alternatively, considering the large gaze shift induced by our tracking target, we can infer that the retinal flow for pursuing the moving target may be perturbing balance control regardless of compensatory head movements. Yet, this leaves open the question of why head-free gaze pursuit of horizontally moving targets compromises standing balance to a greater extent in older than young adults compared to gaze fixation. Future investigations should focus on the effect of gaze pursuit under more challenging balance conditions in older adults and provide a more extensive understanding of the control of dynamic balance while performing complex visual skills. This could result in extracting useful suggestions to improve exercise means and techniques used in fall prevention.

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CRediT authorship contribution statement

Petros Georgiadis: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft. **Konstantinos Chatzinikolaou:** Conceptualization, Methodology, Software, Resources, Visualization. **Dimitrios Voudouris:** Writing – review & editing, Validation, Visualization. **Jaap Van Dieen:** Writing – review & editing. **Vassilia Hatzitaki:** Supervision, Writing – review & editing.

Declaration of Competing Interest

None.

Data availability

Data will be made available on request.

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