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Age induced modifications in the persistency of voluntary sway when actively tracking the complex motion of a visual target

Haralampos Sotirakis
Aristotle University of Thessaloniki

Nick Stergiou
University of Nebraska at Omaha, nstergiou@unomaha.edu

Dimitrios A. Patikas
Aristotle University of Thessaloniki

Vassilia Hatzitaki
Aristotle University of Thessaloniki

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Age induced modifications in the persistency of voluntary sway when actively tracking the complex motion of a visual target

Haralampos Sotirakis, Laboratory of Motor Behavior and Adapted Physical Activity, School of Physical Education and Sport Sciences, Aristotle University of Thessaloniki, Thessaloniki, Greece

Nick Stergiou, Department of Biomechanics and Center for Research in Human Movement Variability, University of Nebraska at Omaha; Department of Environmental, Agricultural and Occupational Health, College of Public Health, University of Nebraska Medical Centre

Dimitrios A. Patikas, School of Physical Education and Sports Science at Serres, Aristotle University of Thessaloniki, Greece

Vassilia Hatzitaki, Laboratory of Motor Behavior and Adapted Physical Activity, School of Physical Education and Sport Sciences, Aristotle University of Thessaloniki, Thessaloniki, Greece

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ABSTRACT

Movement persistency, reflected in systematic cycle to cycle fluctuations of a rhythmical task such as walking or voluntary sway, is compromised with increasing age, making older adults more susceptible to falls. In the present study, we tested whether it is possible to improve rhythmic voluntary sway persistency in old age by actively tracking the complex (i.e. persistent) motion of a visual target. Twenty healthy young and 20 older adults performed 132 cycles of anterior-posterior sway under two conditions: a) self-paced sway and b) sway while tracking the vertical motion of a complex visual target. The persistency of sway cycle amplitude and duration, detected from the center of pressure displacement, was quantified using the Fractal exponent α. We also recorded body kinematics in order to assess the intersegmental coordination that was quantified in the Mean Absolute Relative Phase (MARP) and the Deviation Phase (DPh) between the trunk and the lower limbs. In self-paced sway, older adults showed a lower persistency of cycle duration and a higher MARP and DPh between the trunk and the lower limbs compared to young adults. Tracking the complex visual target motion increased the persistency of cycle amplitude, in young but not in older adults, when compared to the self-paced sway while it decreased the persistency of cycle duration in both groups. The relative phase measures showed a moderate to strong relationship with the persistency of cycle amplitude and duration when older adults swayed in their selfpace. These findings suggest older adults cannot exploit active tracking of the complex visual motion cue to improve voluntary sway persistency. This could be related to the less stable and out of phase intersegmental coordination characterizing rhythmic voluntary sway in old age.

1. Introduction

Adjusting the amplitude of voluntary body weight shifting is an important skill for copying with the postural challenges of every-day actions such as rising from a chair, initiating gait or reaching out. In cyclical tasks such as walking, a persistent movement pattern emerges when a movement parameter (i.e. cycle amplitude or duration) increases or decreases from one cycle to the next in a systematic and non-random order. Conversely, when a movement parameter increases in one repetition and then decreases in the next, the emerged movement pattern is anti-persistent. Persistency characterizes the movement patterns of healthy young adults and seems to be important for resiliency to perturbations [1,2], while an anti-persistent behavior is associated with ageing and disease [3]. This is because a movement system that employs persistency is able to systematically increase or decrease a specific movement parameter, in order to be adaptable to the environmental or task demands [4,5].

In our previous study we showed that healthy young adults can increase the persistency of their anteroposterior voluntary sway amplitude when they actively track the vertical motion of a visual target that has a persistent structure [6]. However, this was achieved at the cost of decreasing the persistency of sway cycle duration. This is because when young individuals track the persistent motion of the visual target while receiving visual feedback of their performance, they match the amplitude of each sway cycle to the concurrent target cycle [7]; conversely, their sway cycle duration is matched to the duration of the previous cycle. Thus, there seems to be a time delay which compromises that temporal features of sway cycle persistency during active tracking of the target motion.

The ability to preserve persistency in movement diminishes with increasing age. Age related decreases in persistency have been reported during gait [8,9] and standing balance [10] but not in other cyclical tasks such as rhythmic voluntary sway. We hypothesize that a similar reduction in persistency would be observed in self-paced, voluntary sway due to the reduced ability of older adults to rhythmically shift their body weight over the limits of the base of support [11]. This in turn is related to ankle muscle strength limitations due to ageing [12], which shift the control of the sway task to the hip muscles [13]. Previous studies confirm that older adults show greater reliance on the hip strategy which results in a more out of phase and variable intersegmental coordination between the lower limbs and the trunk during rhythmic voluntary sway [14,15].

The present study was motivated by the idea that it might be possible to improve voluntary sway persistency in old age by actively tracking the vertical motion of a visual target which reveals a persistent motion structure. Older adults are less able to couple their voluntary sway amplitude to the vertical motion of a visual target, regardless of the form of the visual motion (sinusoidal or complex), when compared to younger adults [16–18]. On the other hand, the ability to synchronize their sway to the target motion is preserved in old age. It remains unclear however whether active tracking of a persistent visual target motion can modulate voluntary sway persistency in older as it does in young adults. We also recorded body kinematics in order to calculate the relative phase between the trunk and the lower limbs and unravel any links between the sway persistency and intersegmental coordination. The following predictions were put forward: a) Older adults would demonstrate a less persistent voluntary sway and more out of phase intersegmental coordination compared to young participants, b) Sway persistency would improve by active tracking of the persistent motion of the visual target and c) Sway persistency is related to intersegmental coordination.

2. Materials and methods

2.1. Participants

Forty healthy volunteers participated in the study. Twenty young adults were recruited among our university's population (age: 27.10 ± 9.15years, height: 170.73 ± 9.40 cm, mass: 68.84 ± 11.48 kg), while 20 older adults (age: 71.63 ± 5.78years, height: 163.5 ± 6.70 cm, mass: 70.38 ± 10.76 kg) were recruited from local community centers for seniors. Participants were informed about the experimental protocol and gave their written consent prior to their participation in the study. Exclusion criteria were a) the presence of any neurological or orthopedic diseases, b) a Mini Mental State Examination score less than 23, and c) failure to complete the task. The experiment was performed with the approval of our institution's ethics review committee in accordance with the Declaration of Helsinki.

2.2. Apparatus, task and stimuli

Participants stood on a force platform (Balance Plate 6501, Bertec, USA, sampling rate: 100 Hz), with a medial-malleolar distance between their feet corresponding to the 10 % of their height, for the acquisition of the Center of Pressure (CoP). A high definition TV screen (LG 60LA620SZA, 60 in.) was positioned 1.5 m in front of them and was centered at eye level. In addition, kinematic data were captured using a 10-camera Vicon system (Vicon Motion Systems, Oxford, UK). Four reflective markers were attached to the participants' skin at four anatomical landmarks: a) the seventh cervical vertebra, b) the sacrum, c) the right trochanter and d) the right external malleolus. The position coordinates of these markers were used to calculate the sagittal angular displacement of each segment, trunk and right lower limb, with respect to the horizontal [34].

Participants were instructed to voluntarily sway back and forth until the completion of 132 cycles (Fig. 1) under 2 conditions: a) voluntary self-paced sway (SELF), and b) rhythmic sway while tracking the complex (i.e. persistent) motion of a visual target constructed using a pink noise process (PINK). The selection of pink noise as the target signal is based on previous studies, showing that it reflects human movement persistency [6,19,20]. The conditions were randomized across subjects to avoid any learning and/or fatigue effects.

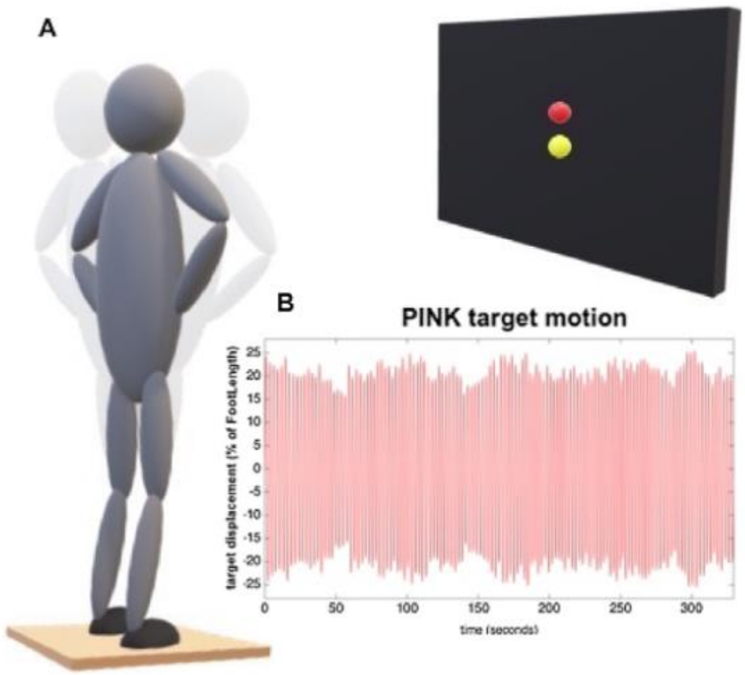

Fig. 1. The experimental setup. A) Participants stood barefoot in front of a TV screen that presented two vertically moving dots. The yellow dot was acquired from the force platform and presented the instantaneous anterior-posterior component of the center of pressure displacement. The red dot represented the target motion to be tracked. B) the signal used to stimulate PINK target.

2.3. Construction of the visual target

Before the main part of the experiment, the participants were instructed to perform 20 voluntary postural sway cycles at their own self-selected amplitude and pace. The range (minima and maxima) of the self-selected sway cycle amplitude and duration were computed from the CoP time series. This information was used to normalize the cycle amplitude and duration of the complex visual target signal. A custom-made MATLAB software was then used to construct the motion of the complex visual target. The visual target was created to simulate the persistent cycle amplitude and duration of voluntary sway that was adjusted to the individual spatiotemporal sway boundaries. For this reason, we used two pink-noise time series, of 132 data points, generated using the “pinknoise” function within MATLAB. The two signals represent the 132 sway cycle amplitudes and durations. The software continued to generate signals and compute the Fractal exponent α, extracted by the Detrended Fluctuation Analysis (DFA), until pink noise process with Fractal exponent α = 1 was ensured. This resulted in two different pink noise signals (signals A and B). Signal A was scaled to the individual's minima and maxima of sway cycle duration, as captured in the 20 voluntary postural sway cycles during the first trial. The Signal B was scaled to the individual's sway cycle amplitude in the exact same way. The complex visual target motion was finally created using a simple sinusoidal function of 132 sinewaves of cycle duration Ai and amplitude Bi, from the two pink noise signals [6].

$$Target = B_i sin\left(2pi\frac{A_i}{uf}t_i\right)$$

Where Ai and Bi elements represent the ith frequency and amplitude values respectively, of the initial pink-noise signals, uf is the updated frequency of the signal on the screen (20 Hz), and t denotes the time vector.

2.4. Data reduction and analysis

2.4.1. Detrended Fluctuations Analysis (DFA)

The Fractal exponent α was extracted using DFA to assess the degree of persistency of postural sway cycle duration and amplitude. The algorithm is described in detail elsewhere [21]. In brief, the raw time series (cycle amplitude and duration) of length N equal with 128 were integrated and separated into boxes of size n. The time series in each box was then detrended and the Root Mean Square (RMS) fluctuation was calculated in each box and averaged across boxes. The algorithm repeated this process for every box size. We selected a range of box sizes from 4 to 32 data-points, as this denoted the minimum standard deviation between different combinations of box-sizes. The exponent α, is acquired as the resultant slope of the log-log plot between the box size and the RMS fluctuation in each box. Values of $\alpha > 0.5$ indicate increased persistency, while an α equal with 1 indicates pink noise; decreasing values indicate a shift towards anti-persistency.

2.4.2. Kinematic analysis

For the evaluation of coordination between body segments, the two dimensional (xz) coordinates of the four markers was used. The body was represented as a double inverted pendulum oscillating around two joints: the ankle and the hip. We used this simplified model as it is widely used in the posture literature [22,23]. The absolute angular position of each segment in the sagittal plane, trunk and right lower limb, was calculated from the four markers as follows:

$$\theta_{segment} = arctan\left(\frac{z_2 - z_1}{x_2 - x_1}\right)$$

Where z and x are the vertical and anteroposterior marker coordinates respectively and indices 1 and 2 refer to the proximal and distal anatomical points of either the trunk (seventh cervical vertebra, sacrum) or the lower limb (greater trochanter, lateral malleolus) segment.

The Continuous Relative Phase (CRP) between the trunk and the lower limb was calculated as a metric of the intersegmental coordination. First, the sway cycles were identified using the lower limb angular position as the reference signal and defining the start of each cycle as the maximum forward leaning position. The phase angle φ was then calculated for each segment as the arctangent of the quotient of angular velocity (calculated by differentiating displacement) and angular deviation in the AP direction [24] (Fig. 2):

$$\varphi(t) = arctan\left(\frac{\dot{x}(t)}{x(t)}\right)$$

The CRP defines the spatiotemporal phasing relationship between the two interacting segment motions (i.e. their coordination) calculated by the difference between the respective phase angles of the two segments:

$$CRP = \varphi_{limb} - \varphi_{trunk}$$

Finally, the CRP values of each cycle were normalized to 100 % of the sway cycle using linear interpolation and ensemble CRP curves were calculated and averaged across trials. The Mean Absolute Relative Phase (MARP) is calculated by averaging the 100 data points of the mean ensemble curve. MARP values between 0◦and 180◦ were retrieved. The Deviation Phase (DPh) was calculated by averaging the standard deviations of the ensemble curve data points.

Functionally, a lower MARP value indicates an in-phase coordination and indicates that the two segments are synchronously moving in the same direction [22]. This means that the body oscillates like an inverted pendulum around the ankle joint. Alternatively, CRP values higher than 20˚reflect an "out of phase" coordination and indicate that the trunk and the lower limb are synchronously oscillating in an opposite direction, revealing a hip strategy. A lower DPh means that the relative phase between the two segments is less variable and thus more stable [24,25].

2.5. Statistical analysis

All dependent variables were tested for violation on sphericity using the Mauchly's test for equality of variances and for normality of distribution using the Shapiro-Wilk's test. The Mauchly's test did not indicate any violations of the sphericity ($p > 0.05$) and all dependent variables were found to be normally distributed ($p > 0.05$). The age-related differences in the persistency of sway cycle amplitude (αamp) and duration (αdur) as well as the lower limb-trunk MARP and DPh were analyzed across the two experimental conditions. We used a two (conditions) by two (age-groups) ANOVA with repeated measures in the condition factor for all dependent measures. Significant interactions or main effects where further analyzed using pairwise comparisons between factor levels with Bonferroni adjustment for multiple comparisons. Estimates of effect size are noted with η2 and significance level has been set to $p < 0.5$.

Furthermore, the relationship between postural sway persistency and intersegmental coordination was first assessed using Pearson Correlation. In detail, MARP, DPh, αamp, αdur were included in the correlation analysis. A simple linear regression analysis was performed, between significantly correlated variables. All statistical analyses were performed in SPSS (version 25).

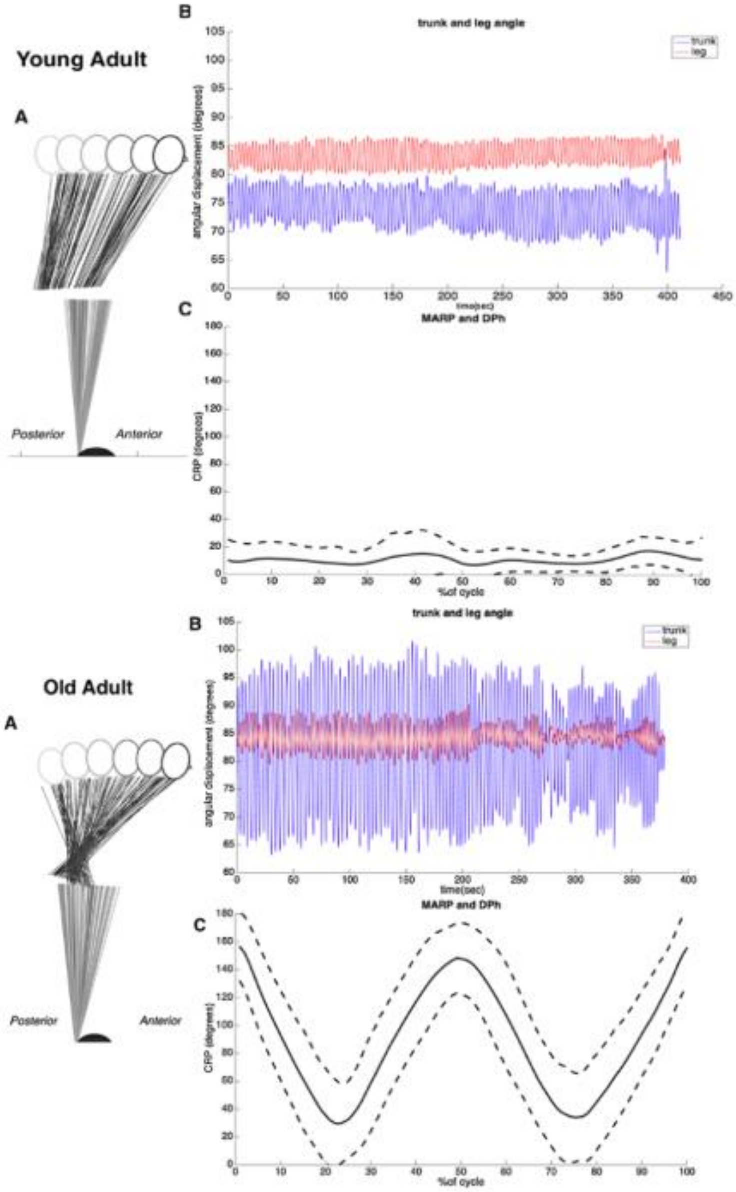

Fig. 2. Representative data for a young and an older participant during self-paced sway. A) Stick figure diagram of the trunk (black) and lower limb (grey) motion reconstructed for 4 postural sway cycles. A larger and more out of phase trunk relative to lower limb rotation is evident for the older participant. B) Angular displacement of trunk (blue) and lower limbs (red) for the 128 sway cycles shows that the older participant uses a greater trunk rotation, compared to the young participant. C) Mean Absolute Relative Phase (MARP, continuous line) and its standard deviation (DPh, dashed line) plotted as percent of cycle duration for the 128 sway cycles, denoting an out of phase and more variable intersegmental coordination for the older adult.

3. Results

The mean postural sway cycle amplitude in self-paced sway was 64%(±7.6) of foot-length for young adults and 39 %(±9.3) for older adults. The mean sway cycle duration was 3160 ms(±530) in young and 3175 ms(±590) for old adults.

3.1. Effects of age and tracking

3.1.1. Fractal exponent α of cycle amplitude and duration

The Fractal exponent α of sway amplitude (αamp, Fig. 3A) significantly decreased in the older adults as compared to the young ($F_{1,38} = 7.585$, $p = 0.009$, $\eta^2 = 0.166$). No effect of condition was noted. A group by condition interaction was found ($F_{1,38} = 5.602$, $p = 0.023$, $\eta^2 = 0.128$) which indicated that αamp increased only in young adults when they tracked the complex visual target ($p = 0.029$). The Fractal exponent of cycle duration (αdur) decreased in the older adults as compared to the young ($F_{1,38} = 9.667$, $p = 0.004$, $\eta^2 = .203$) (Fig. 3B), while this decrease was evident in both age-groups in the PINK condition as compared to the SELF ($F_{1,38} = 14.182$, $p = 0.001$, $\eta^2 = 0.272$). No group by condition interaction was noted for αdur.

3.1.2. Lower limb-trunk relative phase

MARP (Fig. 3C) was significantly larger in the older adults as compared to young adults ($F_{1,38} = 9.309$, $p = 0.005$, $\eta^2 = 0.225$). When participants tracked the complex visual target, they significantly increased the lower limb-trunk MARP ($F_{1,38} = 6.679$, $p = 0.015$, $\eta^2 = .173$) as compared to the SELF condition. No group by condition interaction was noted. DPh (Fig. 3D) also increased in the older adults as compared to the young ($F_{1,38} = 15.412$, $p = 0.000$, $\eta^2 = 0.325$). The lower limb-trunk DPh increased when tracking the complex target compared to the self-paced condition ($F_{1,38} = 9.068$, $p = 0.005$, $\eta^2 = .221$) in all groups, revealing no interaction.

3.2. Correlation analysis

The Pearson correlation coefficients between the persistency measures (αamp, αdur) and the intersegmental coordination indices (lower limb-trunk MARP and DPh) are noted in Fig. 4. The correlation analysis was performed separately for the young and older adults in the SELF and PINK conditions.

In older adults, increased MARP values were moderately or strongly correlated with decreased Fractal exponent for cycle amplitude ($r=- 0.510$). Increased DPh were also moderately or strongly correlated to decreased αamp ($r=-0.520$) and decreased αdur ($r=-0.505$) in older adults. Contrarily, young adults revealed weak and non-significant correlations between the sway persistency and intersegmental coordination measures.

When tracking the visual target motion, an increase MARP was moderately related to higher values of the Fractal exponent α of duration ($r=-0.539$) for older adults. Young adults revealed weak, non-significant correlations between the sway persistency and intersegmental coordination measures.

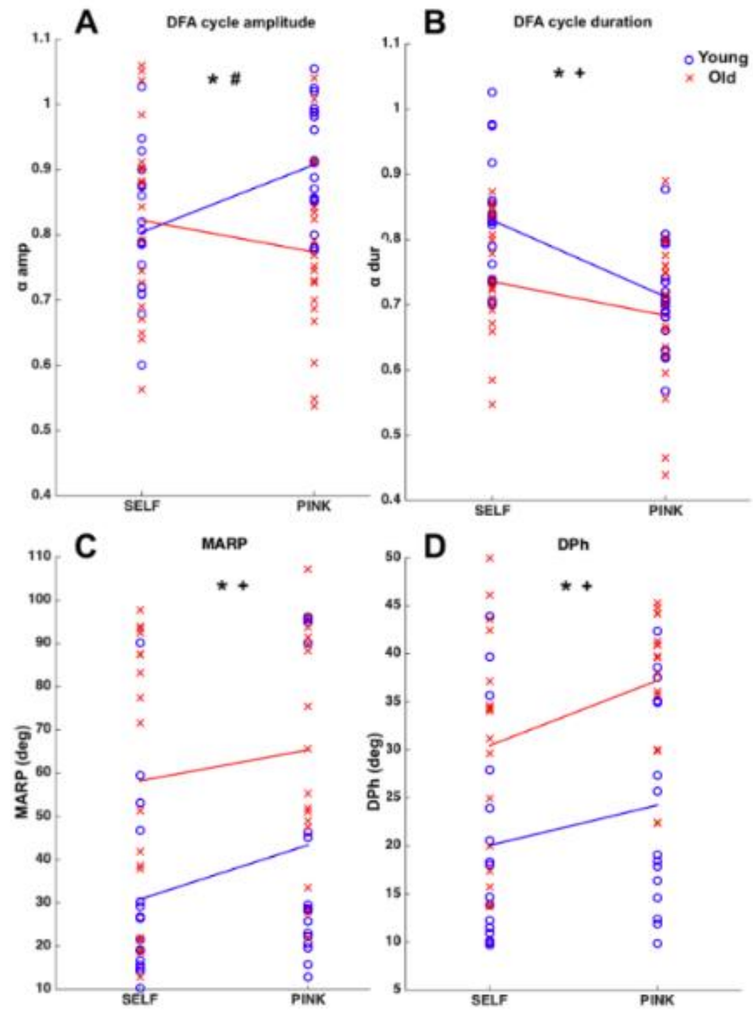

Fig. 3. Fractal exponent α for cycle amplitude (A) and duration (B), Mean Absolute Relative Phase (C) and Deviation Phase (D), for young (blue circles) and older (red Xs) adults. Lines represent the group change between the two conditions. (*): significant difference between groups. (+): significant difference between sway conditions. (#): interactions between group and sway condition.

4. Discussion

Self-paced voluntary sway was less persistent and demonstrated a more out of-phase coordination between the trunk and the lower limbs, in older compared to young adults. Contrary to our prediction, tracking of the complex (i.e. persistent) target motion did not improve the persistency of cycle amplitude fluctuations in older as it did in young participants. Interestingly, a less persistent self-paced sway was related to a more variable and out of phase trunk-limb coordination in older but not in young participants.

4.1. Ageing affects postural sway persistency

The persistency of the sway cycle duration was lower in older (Fractal exponent α~ 0.72) as compared to young adults (α~0.83). This is in line with evidence from the walking literature showing reduced stride duration persistency as a result of ageing [3]. It has been suggested that a less persistent walking pattern is associated with the older adults' reduced ability to overcome perturbations [1].

Surprisingly, the persistency of sway cycle amplitude did not reveal differences due to age. Older adults were expected to show an antipersistent cycle amplitude, with increases followed by decreases and vice versa. This hypothesis stems from the knowledge that with increasing age, the sway area approximates the geometrical boundaries of stability [11]. Therefore, cycle by cycle amplitude adjustments (i.e. increases followed by decreases) are necessary for older adults to control sway amplitude and avoid falling. Instead, the results of the present study suggest that older adults selected to voluntarily sway in a reduced cycle amplitude (39 % of foot-length) compared to young adults (64 % of foot-length), which possibly allowed them to accommodate systematic cycle amplitude adjustments and thus preserve a persistent pattern of sway cycle amplitude. Previous studies from our and other laboratories [16–18] confirm that even when the sway task visually imposes a specific cycle amplitude, older adults are less able to match their sway to the specific spatial constraint.

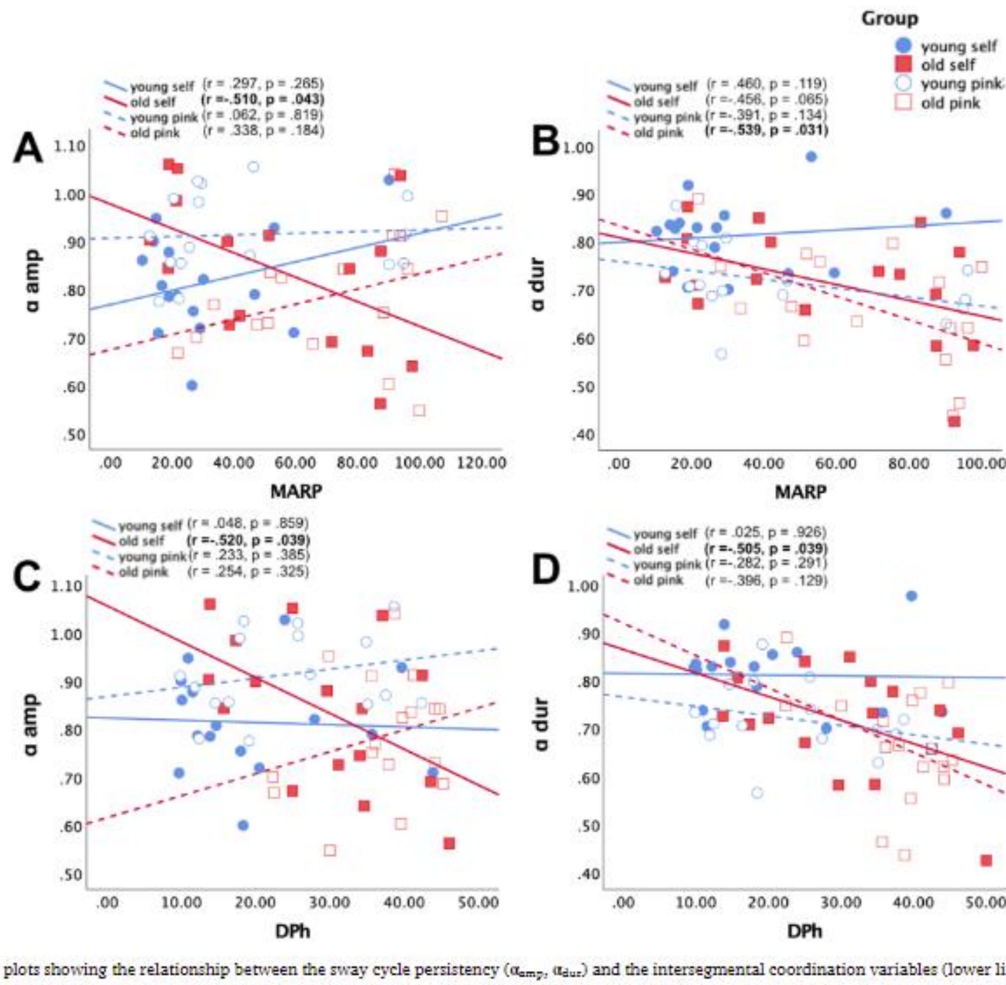

Fig. 4. Scatter plots showing the relationship between the sway cycle persistency (α_{amp}, α_{dur}) and the intersegmental coordination variables (lower limb-trunk MARP and DPh). The blue circles represent young adults and squares the older adult group (filled shapes: SELF, open shapes: PINK). The regression lines in blue and red color represent young and older adults respectively (continuous lines: SELF, dashed: PINK).

4.2. Tracking of the complex motion of a visual target does not improve sway persistency in older adults

In the current study we introduced a complex visual target motion, as a guiding stimulus in order to improve the persistency of voluntary sway. We constructed the target motion to contain both persistent sway cycle amplitudes and durations, based on a pink noise signal generation process resembling the persistency of biological cyclical motion (e.g. gait [19], voluntary postural sway [6]). Our results show that young adults were able to increase the persistency of sway cycle amplitude during active target tracking, approximating the persistency of the target motion ($\alpha = 0.91$). However, contrary to our prediction, this was not the case for older adults who did not change their cycle amplitude persistency when tracking the complex target motion. Modulating sway amplitude persistency by actively tracking a complex visual motion cue, requires matching the ongoing sway cycle amplitude to the concurrent target cycle amplitude [6]. The ability to couple postural sway amplitude to the amplitude of the target motion diminishes with ageing [16–18], which may explain why older adults were unable to improve the persistency of sway cycle amplitude during tracking. In addition, the absence of a modulation may reflect the decreased ability to systematically increase sway amplitude in order to reach the geometrical boundaries of stability. This does not seem to be the case however, because in the current experiment the amplitude of the target motion was normalized to the mean cycle amplitude of self-paced voluntary sway.

The persistency of sway cycle duration, on the other hand, decreased in both young and older adults when tracking the complex target motion. Based on our previous study findings [16], it seems that participants, regardless of age, adjusted the duration of the current sway cycle, based on the duration of the previous target cycle. This introduces a time delay that reduces the persistency of cycle durations compared to self-paced sway. The down-modulation was similar between young and older adults, since the ability to synchronize (i.e. temporal coupling) sway to the target motion is not compromised with increasing age [16].

4.3. A less persistent sway is related to a less stable and out of phase intersegmental coordination in old age

One reason why older adults could not match their sway amplitude to the amplitude of the target motion could be their age-related alterations in intersegmental coordination during rhythmic voluntary sway. Older adults swayed in an out of phase and more variable coordination between the lower limbs and the trunk compared to young adults. This altered coordination pattern was moderately to strongly associated with a less persistent self-paced sway. An out of phase coordination between the trunk and the lower limbs indicates that older adults swayed around both the ankle and the hip joint as a double, rather than a single inverted pendulum (Fig. 2) possibly due to their reduced ability to control the amplitude of sway using the ankle muscles [12,13]. This strategy, while it reduces the radius of gyration and therefore the body’s momentum during voluntary sway, it constraints the center of pressure motion within a limited boundary of the base of support due to the greater shear than vertical forces applied to the ground [26,27]. It is therefore more difficult to control the anteroposterior

CoP motion over the base of support and precisely match its amplitude to the visual target amplitude when the body sways like a double instead of a single inverted pendulum. These findings complement previous work showing that a double instead of a single inverted pendulum voluntary sway motion impedes interpersonal coupling mediated through light fingertip touch between the two partners [23].

An age-induced deficiency in the coupling of voluntary sway amplitude to the visual target motion is confirmed by previous studies [16–18]. On the positive side, older participants are able to improve the spatial coupling to a visual target motion by decreasing upper trunk rotation and shifting the control of the task to the lower limbs [14]. These observations provide some promise that it might be possible to improve sway amplitude persistency by shifting the control of the sway task to the distal ankle muscles while maintaining a more stable and in phase coordination between the trunk and the lower limbs. We suggest that such a shifting strategy would be more critical when the target moves unpredictably, as this was the case of the present study.

5. Conclusions

In summary, our results stress the role of intersegmental coordination in voluntary sway persistency in old age. It seems that older adults' less persistent voluntary sway is related to a more variable (i.e. less stable) and out of phase intersegmental coordination. This looser coordination prevents coupling to the complex visual target motion during active tracking eliminating any possible impact on cycle amplitude persistency of voluntary sway. Our results suggest that improving the coordination between the lower and upper body should be a central goal of balance rehabilitation regimes in old age. However, these results have to be interpreted with caution, since only one trial of 132 cycles of guided postural sway was performed. Further investigation is needed, using longer protocols of visual guidance to investigate whether complex visual targets can be used to modulate postural sway persistency in older adults. Addressing these questions could significantly contribute to the design of targeted intervention programs aiming to improve static and dynamic balance in old age.

CRediT authorship contribution statement

Haralampos Sotirakis: Investigation, Formal analysis, Writing - original draft, Funding acquisition. Nick Stergiou: Writing - review & editing, Funding acquisition. Dimitrios A. Patikas: Writing - review & editing. Vassilia Hatzitaki: Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors report no declarations of interest.

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