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UPPER BODY ACCELERATIONS DURING PLANNED GAIT TERMINATION IN
YOUNG AND OLDER WOMEN

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**Abstract**

Transitory tasks, such as gait termination, involve interactions between neural and biomechanical factors that challenge postural stability and head stabilization patterns in older adults. The aim of the study was to compare upper body patterns of acceleration during planned gait termination at different speeds between young and older women. Ten young and 10 older women were asked to carry out three gait termination trials at slow, comfortable and fast speed. A stereophotogrammetric system and a 15-body segments model were used to calculate antero-posterior whole-body Center of Mass (AP CoM) speed and to reconstruct the centroids of head, trunk and pelvis segments. RMS of three-dimensional linear accelerations were calculated for each segment and the transmission of acceleration between two segments was expressed as a percentage difference. Older women reported lower AP CoM speed and acceleration RMS of the three upper body segments than young women across the three speed conditions. A lower pelvis-to-trunk attenuation of accelerations in the transverse plane was observed in older compared to young women, and mainly in the medio-lateral direction. As possible explanations, older women may not need to reduce acceleration as young women because of their lower progression speed and the subsequent acceleration at upper body levels. On the other hand, older women may prioritize a decrease in the whole body progression speed at expense of the involvement of upper body segments. This limits the attenuation of the accelerations, particularly in the transverse plane, implying an increased dynamic unbalance in performing this transitory task.

**Keywords**: transitory task; dynamic balance; elderly; upper body; acceleration; locomotion

**Introduction**
Stabilization of the head with respect to the environment is fundamental to preserve whole body balance during locomotion (Cromwell et al., 2001; Mulavara and Bloomberg, 2003; Pozzo et al., 1990). As an inertial guide platform, head stability helps to maintain gaze by optimizing input from visual, vestibular and somatosensory systems (Cromwell et al., 2004; Pozzo et al., 1990). This mechanism is threatened over each gait cycle by the heel strike that provokes a sudden impact acceleration, which is transmitted from the lower body structures to the head (Cappozzo, 1991; Mulavara and Bloomberg, 2003). During level walking, young adults adopt a “head stabilization in space” strategy performed at the upper body level and aimed at attenuating the acceleration transmitted from pelvis to head, following a strain-reducing criterion (Cappozzo, 1991).

Head stability is influenced by gait speed (Hylton B Menz et al., 2003; Moe-Nilssen, 1998), with increasing upper body accelerations at fast speed (Hirasaki et al., 1999; Kavanagh et al., 2006; Hylton B Menz et al., 2003). In fact, older individuals that typically adopt a slowness strategy by reducing walking speed and head accelerations in the antero-posterior (AP) and vertical (VT) directions, but not in the medio-lateral (ML) direction, compared to young individuals during level walking (Mazzà et al., 2008; Hylton B. Menz et al., 2003). This reduced attenuation of ML acceleration may further deteriorate in more challenging circumstances than walking, leading to augmented head lateral acceleration and, thus, to an unstable reference platform for vision and vestibular systems (Lord et al., 1996).

Transitory locomotor tasks, in particular, involve complex interactions between neural and mechanical factors which may challenge upper body stability (Laudani et al., 2006) and whole-body balance to a greater extent than unconstrained walking (Nagano et al., 2013). This challenge may help to explain why the number of falls in older individuals are frequent during locomotor transitions such as gait termination (Sparrow and Tirosh, 2005; Winter, 1995). From a biomechanical perspective, gait termination is defined as a transition between steady-state walking and upright standing, which requires a minimal level of extensor torque in lower limb joints and an adjustment of foot placement: both factors are aimed at keeping the Center of Mass (CoM) behind
the feet center of pressure (CoP). This regulation of CoM-CoP vector generates decelerating forces that are therefore able to reduce forward speed and terminate gait (Jian et al., 1993). The literature reports that older adults have a diminished activation of lower limb extensor muscles when terminating gait in response to a visual cue (Tirosh and Sparrow, 2005, 2004), thus outlining a reduced involvement of lower body without taking into account the role of the upper body in performing the gait termination task. In fact, as the upper body represents 2/3 of the whole body mass, its movement could effectively help in completing the task by controlling the CoM position and, therefore, peculiar acceleration patterns could be expected for this transitory task. To the authors’ knowledge, there is no study in the literature looking at the pattern of upper body accelerations during gait termination and how these accelerations are transmitted through the body along the three directions of space. These quantities are directly related to dynamic balance and have the potential to unveil peculiar motor strategies adopted by either young or older individuals (Mazzà et al., 2008).

The aim of this study was to compare upper body patterns of acceleration during planned gait termination between young and older women. It was hypothesized that older women might present lower attenuation of acceleration from pelvis to head than young, especially in the ML direction.

**Methods**

**Participants**

Ten healthy young women (age: 23.1 ± 1.1 years; height: 1.66 ± 0.06 m; body mass: 56.9 ± 6.6 kg) and ten healthy and independent community-dwelling older women (age: 73.8 ± 2.4 years; height: 1.60 ± 0.06 m; body mass: 62.1 ± 13.6 kg) volunteered to participate in this study. The homogeneity of the two groups with respect to the body mass parameter was verified through an independent sample t-test (p>0.05). The age groups were divided according to the following inclusion criterion: 20-30 years old for the young and 70-80 years old for the older group. Exclusion
criteria for this study were any history of neurological or musculoskeletal disorders and use of any drug that would affect balance or gait ability. For ensuring subjects eligibility, both groups answered a health-screening questionnaire before undergoing the experimental protocol. Written informed consent was provided by all participants and ethical approval was given by the institution ethics committee.

Equipment and experimental procedure

A seven-camera stereophotogrammetric system (Vicon MX3, Oxford, UK) was used to reconstruct the 3D position of 35 retro-reflective spherical markers located on the subject skin (Gutierrez et al., 2003; Kadaba et al., 1990) with a sampling rate of 100 samples/s. A 15-body segments 3D model (Vicon Plug-in-gait full-body model) (Gutierrez et al., 2003; Kadaba et al., 1990) was used to calculate kinematic parameters and CoM trajectory. The relevant kinematic data were filtered using a second order low-pass Butterworth filter with a cut-off frequency of 30 Hz.

Participants were asked to walk in a straight line and to stop with both feet in parallel upon a pre-set target area on the ground (length 60 cm; width 40 cm) in the middle of a 10 m walkway. The selected walkway length was considered sufficient to reach the steady-state walking velocity and to terminate the gait (Breniere and Do, 1986). Once stopped, they were asked to maintain an upright standing posture for at least 3s. The trials were performed at three different self-selected speeds (slow, comfortable and fast) in a randomized fashion. Instructions were given by associating each condition to the everyday activities (Thomas et al., 2007): walking during relaxed window-shopping (slow speed); walking in a relaxed mood (comfortable speed); walking as when late for an appointment (fast speed). The participants performed three consecutive familiarization trials per speed condition to set the starting position in order to ensure a minimum of four steps before approaching the target area with the right foot. In case the participant failed to place both feet on the pre-set target area, the trial was discarded and then repeated until a total of three valid trials was obtained for each speed condition (Menant et al., 2009).
Data analysis

Gait termination was subdivided as follows: Approaching, Braking and Stabilization Phases (Jian et al., 1993; O’Kane et al., 2003). The Approaching Phase consisted of the last stride prior to stopping from the first right heel contact (RHC1) to the second right heel contact (RHC2) of the stance limb (O’Kane et al., 2003) (Fig.1). The Braking Phase ranged from RHC2 to the left heel contact (LHC1); at the end of this phase both feet are on the pre-set target area. The Stabilization Phase lasted from LHC1 to the time instant in which the body attains the stable position (FS). This was assumed when CoM progression speed was less than 0.05 m/s (Meier et al., 2001). Each phase duration was calculated and used for statistical comparisons between groups. Mean CoM speed in the AP direction during each phase was calculated from the whole body CoM position in space and used as an estimate of the progression speed.

FIG. 1 HERE

Given the reliability of stereophotogrammetric system (Thies et al., 2007), head, upper trunk (hereinafter referred to as trunk) and pelvis three-dimensional linear acceleration were obtained from the segment centroids trajectory as obtained from aforementioned biomechanical model. RMS of acceleration in AP, ML and VT directions of head (RMS$_H$), trunk (RMS$_T$) and pelvis (RMS$_P$) were then computed using Matlab (Mathworks, Inc., USA).

To investigate how the acceleration was transmitted from pelvis to trunk (C$_{PT}$), from trunk to head (C$_{TH}$), and from pelvis to head (C$_{PH}$), the following coefficients were defined for each axis (Mazzà et al., 2008):

$$C_{PT} = \left(1 - \frac{RMS_T}{RMS_P}\right) \times 100$$

$$C_{TH} = \left(1 - \frac{RMS_H}{RMS_T}\right) \times 100$$
A positive coefficient indicates an attenuation of acceleration from lower to upper body segment and, conversely, a negative value indicates bottom-up increase in the acceleration. The coefficients of attenuation have been shown to be independent of walking speed during gait in young and elderly women (Mazzà et al., 2008).

Statistical analysis

The normal distribution of data was tested using a Shapiro-Wilk test and the presence of outliers was inspected. The effects of a within-subjects factor (speed: slow, comfortable and fast) and a between-subjects factor (age: young and older) on mean AP CoM speed, duration of each phase and coefficients of attenuation were investigated using a repeated measures (RM) ANOVA. Given the possible confounding effect of progression speed on RMS of upper body acceleration, mean AP CoM speed was included as a covariate in the statistical analysis of RMS accelerations by carrying out a RM ANCOVA. This analysis adjusted the group means at the average value of the covariate, thus allowing a comparison at a level of the covariate that was the same for each group. Whenever there was a significant effect of the age factor, post-hoc comparisons with Bonferroni correction were performed to investigate at which speed condition there was a difference between groups. In the case of a significant interaction between the two factors, pairwise comparisons with Bonferroni correction were performed and the variable trend across the three speed conditions in the two groups was evaluated. Statistical results of pairwise comparisons were shown and grouped when required. SPSS 22.0 was used for statistical analysis (Chicago, IL, USA) and the significance level \( \alpha \) was set to 0.05.
Both mean AP CoM speed and duration in each phase are reported in Table 1. Older women had lower AP CoM speed than young women in the Approaching and Breaking Phases at each of the three speeds (F>23.384; p<0.001) and in the Stabilization Phase only at fast speed (F=10.266; p<0.005). While a progressive increase of AP CoM speed was reported between speed conditions at each of the three phases in young women, such increase was observed only at the Approaching Phase in older women. The abovementioned difference in AP CoM speed between groups was also investigated within the context of the stability region defined by Pai and Patton (Pai and Patton, 1997), providing the relative plots as supplementary material (Fig.S1). Moreover, older women had longer phase duration than young women only during the Approaching Phase at each of the three speed conditions (F=6.732; p<0.05). Phase duration decreased across conditions in both groups during the Approaching and Braking Phases (F>40.950; p<0.001), but increased during the Stabilization Phase (F=20.852; p<0.001) (Table 1).

TABLE 1 HERE

**Approaching Phase**

The RM ANCOVA showed that older women had lower AP RMS<sub>P</sub> than young women (F>7.083; p<0.05) at slow and comfortable speed (Fig.2a and b). Older women showed also lower ML RMS<sub>P</sub> than young women at each of the three speed conditions (F>5.079; p<0.05) (Fig.2g, h and i). Moreover, older women displayed lower ML C<sub>PH</sub> and C<sub>PT</sub> at all self-selected speeds (F>19.016; p<0.001) (Fig.2j, k and l) and AP C<sub>PT</sub> at slow speed (F=4.481; p<0.05) (Fig.2d) compared to young women.

A significant age by speed interaction at pelvis in ML direction and the subsequent post-hoc analysis revealed that young women increased RMS across speed conditions (F>36.790, p<0.05), whereas older women displayed no differences in ML RMS<sub>P</sub> (Fig.2j, h and i). Significant interaction effects were also found in AP C<sub>PH</sub>, C<sub>PT</sub> and C<sub>TH</sub> (F>3.773; p<0.05), with young women displaying
decreasing coefficients and older women showing no differences in the coefficient values across speed conditions (Fig.2d, e and f).

Braking Phase

RMS acceleration and coefficient of attenuation of Braking Phase at the three speed conditions in both groups are reported in Table 2. RM ANCOVA showed that older women had lower AP, ML and VT RMS at pelvis (F>22.430, p<0.005; F=26.525, p<0.05; and F>20.632, p<0.05, respectively) and VT RMS at trunk and head (F>25.281; p<0.001) compared to young women at different speed conditions. Furthermore, older women displayed lower CPH and CPT than young women at slow and comfortable speeds in AP direction and at comfortable and fast speeds in ML direction.

Significant interaction effects on RMS acceleration at pelvis, trunk and head in VT direction (F>9.087; p<0.005) and at trunk and head in AP direction (F>11.554; p<0.001) were observed. The post-hoc analysis revealed that young women had increasing RMS across speed conditions, while older women did not report any changes. In addition, significant interactions were found in AP CPH and CPT (F>18.896; p<0.001), with young women having decreasing coefficients as speed level increased. In ML direction, CPT was higher at slow than comfortable speed in older women, while there was no difference in young women. ML CTH was higher at fast than slow and comfortable speed conditions in young women, with no differences in older women. ML CPH was lower at slow than at fast speed in young women, while it was higher at slow than comfortable and fast speeds in older women (Table 2).

Stabilization Phase
RM ANCOVA revealed that older women had higher AP RMS$_p$ at comfortable and lower AP RMS$_T$ and RMS$_H$ at slow and fast speed conditions compared to young women ($F>18.785; p<0.05$) (Fig.3b, a and c, respectively). Older women showed also higher ML RMS$_H$ than young women at fast speed ($F>23.903; p<0.05$) (Fig.3i). Higher AP C$_{PH}$, C$_{PT}$ and C$_{TH}$ at each of the three speed conditions ($F>9.155; p<0.05$) (Fig.3d, e and f) and lower ML C$_{PH}$ and C$_{TH}$ at fast speed were reported ($F>12.182; p<0.05$) (Fig.3l). No interaction effects were found in the same parameters.

FIG. 3 HERE

Discussion

The main finding of this study was that older women showed lower acceleration RMS and attenuation of acceleration from pelvis to head than young, with specific patterns in each gait termination phase. In the Approaching Phase, older women showed lower ML accelerations at pelvis than young women and, associated to this, lower attenuation from pelvis to trunk on the same axis. In the Braking Phase, older women exhibited lower pelvis-to-trunk attenuation even in the AP direction. Finally, in the Stabilization Phase, older women effectively reduced AP acceleration from pelvis to head through a pelvis-to-trunk attenuation strategy, but increased ML acceleration across upper body segments more than young women at fast speed.

At each speed condition, older women showed lower AP CoM speed in the Approaching and Braking Phases and lower duration of the Approaching Phase compared to young women (Table 1). In addition, the two groups exhibited different braking actions resulting in different AP CoM speeds across the three conditions in the last two phases (Table 1). These differences can be attributed to the age-related decline of neuromuscular function (Laudani et al., 2013) and are in line with previous studies on gait termination (Tirosh and Sparrow, 2005). Such a “slowness” strategy has been previously reported as a compensation for balance deficits in healthy and pathological older adults during gait termination (Meier et al., 2001; Menant et al., 2009; Tirosh and Sparrow, 2004).
and as an improvement of upper body stabilization in elderly during walking (Menz et al., 2003). In this study, including the progression speed in the statistical analysis allowed to rule out that any difference in acceleration at head and trunk level could be attributed to the lower walking speed in the older compared to the young group. Instead, it was possible to identify significantly lower AP and ML acceleration at pelvis in older women than in young women, thus suggesting a different pattern of acceleration attenuation across the upper body levels between the two groups regardless of the different progression speed.

In both Approaching and Braking Phases, older women did not counteract the ML acceleration increase from trunk to head by adopting a pelvis-to-trunk attenuation strategy as young women did, resulting in higher acceleration at head than at pelvis along the ML direction. In studies of unplanned gait termination triggered by a visual cue, the higher incidence of two-step stopping strategies in the elderly has been associated with decreased ML balance due to the age-related reduced activation of gluteus medius (Tirosh and Sparrow, 2005, 2004). The results of the present study add to the overall picture by including upper body data and suggesting that the decreased attenuation of ML accelerations could be associated with the reported ML unbalance in older women.

During the Braking Phase, older women showed a decreased attenuation of acceleration from pelvis to both upper segments in the AP direction only at comfortable and slow speeds. Thus, while older women adopted the same damping pattern at each speed condition, young women reduced this pattern as progression speed increases, outlining a significant increase of head acceleration at fast speed as in level walking (Hirasaki et al., 1999; Kavanagh et al., 2006; Hylton B Menz et al., 2003). Moreover, it is noteworthy that this different attenuation of AP acceleration occurred in the Breaking Phase when the main reduction of AP CoM speed is observed (Jian et al., 1993). The reduced AP head stabilization in the older women might, therefore, be related to a higher prioritization of the deceleration of whole body mass at the expense of the acceleration damping between upper body segments. Although this altered damping pattern could undermine head
stabilization, thus producing an unstable reference platform for all the sensory systems that are essentials for balance control, this aspect of gait termination is still poorly investigated.

In the Stabilization Phase, older women showed an AP acceleration attenuation from pelvis to head and, specifically, from pelvis to trunk at each of the speed conditions, whereas in young women an acceleration increase from pelvis to trunk was observed. From a biomechanical point of view, because of the stop at lower extremities and pelvis level, young women experienced higher RMS acceleration at the upper levels due to the coupled effect of inertia and higher progression speed compared to the older women. Although a control for the effect of progression speed on acceleration has been performed, its effect on the transmission of acceleration across upper body segments clearly persists at each of the speed conditions, as shown by the negative values of $C_{PT}$ and head in AP direction in young women. On the other hand, older women increased acceleration from pelvis to head along ML direction more than young women, with head acceleration being higher at fast speed. This confirms the previously reported ML unbalance in older women and outlines the role of a high progression speed on the observed accelerations. In older women, the different pattern of acceleration damping between AP and ML directions suggests an axis-related priority level given to the control of upper body acceleration during this quasi-static phase of gait termination, with ML being controlled lesser than AP direction as during walking (Latt et al., 2008).

In conclusion, older women adopted the so called “slowness strategy” during planned gait termination, which is likely to improve their balance. However, they showed reduced attenuation of the acceleration at different upper body levels, particularly from pelvis to trunk. The overall lower damping capacity of trunk may provoke a greater unbalance with respect to young women and be ascribed to the fact that: $i$) older women do not have to reduce acceleration as young women because of their lower progression speed; $ii$) older women give higher priority to the decrease of whole body progression speed, thus limiting the attenuation of the accelerations between upper body segments. Nevertheless, trunk appears to play a major role in the head stabilization process,
which should be taken into account in designing training interventions aimed at preventing falls in older individuals.

Acknowledgments: The authors wish to thank Dr. Amy Maslivec for her support in data acquisition.

References


### TABLES

#### Table 1.
AP average speed of whole body CoM (m·s⁻¹) and phase duration of gait termination at slow, comfortable and fast speed conditions for the two groups (mean (SD)). * significantly different from young (p <0.05). † significantly different from the two other speed conditions (p <0.05).

<table>
<thead>
<tr>
<th></th>
<th>Slow</th>
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<tbody>
<tr>
<td></td>
<td>Older</td>
<td>Young</td>
<td>Older</td>
</tr>
<tr>
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<tr>
<td>(m·s⁻¹)</td>
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<td>0.08 (0.03)†</td>
<td>0.10 (0.03)</td>
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<tr>
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<td>(s)</td>
<td></td>
<td></td>
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<tr>
<td>Approaching</td>
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<td>1.29 (0.18)†</td>
<td>1.33 (0.35)*†</td>
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<td>0.40 (0.15)†</td>
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#### Table 2.
RMS acceleration and coefficient of attenuation in AP, ML and VT directions during the Braking Phase at slow, comfortable and fast speeds (mean (SD)). * significantly different from young (post-hoc comparisons of significant age effect; p <0.05). † significantly different from the two other speed conditions (post-hoc comparisons of significant age x speed effect; p <0.05).

<table>
<thead>
<tr>
<th>Braking Phase</th>
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<td>1.26 (8.70)†</td>
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<tr>
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</tr>
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<td>-17.27 (16.54)‡</td>
<td>-8.66 (10.16)‡</td>
<td>-9.14 (17.15)‡</td>
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</table>
FIGURE CAPTIONS

Fig. 1
Subject’s foot positioning and gait termination events for phase definition

Fig. 2
RMS of pelvis, trunk and head acceleration, and coefficient of attenuation in AP and ML directions during the Approaching Phase at slow (a, d, g, j), comfortable (b, e, h, k) and fast (c, f, i, l) speed conditions (mean ± S.D.). * significantly different between groups (post-hoc comparisons of significant age effect; p <0.05); † significant age × speed interaction (post-hoc comparisons; p <0.05).

Fig. 3
RMS of pelvis, trunk and head acceleration, and coefficient of attenuation in AP and ML directions during the Stabilization Phase at slow (a, d, g, j), comfortable (b, e, h, k) and fast (c, f, i, l) speed conditions (mean ± S.D.). * significantly different between groups (post-hoc comparisons of significant age effect; p <0.05).