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Head orientation and gait stability in young adults, dancers and older adults

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ABSTRACT

Background: Control of body orientation requires head motion detection by the vestibular system and small changes with respect to the gravitational acceleration vector could cause destabilization.
Research question: We aimed to compare the effects of different head orientations on gait stability in young adults, dancers and older adults.
Methods: Three groups of 10 subjects were evaluated, the first composed of young adults (aged 18–30 years), the second composed of young healthy dancers under high performance dance training (aged 18–30 years), and the third group composed of community-dwelling older adults (aged 65–80 years). Participants walked on a treadmill at their preferred speed in four distinct head orientation conditions for four minutes each: control (neutral orientation); dynamic yaw (following a target over 45° bilaterally); up (15° neck extension), and down (40° neck flexion). Foot and trunk kinematic data were acquired using a 3D motion capture system and the gait pattern was assessed by basic gait parameters (step length, stride width and corresponding variability) and gait stability (local divergence exponents and margins of stability). Main effects of conditions and groups, as well as their interaction effects, were evaluated by repeated-measures analysis of variance.
Results: Interactions of group and head orientation were found for both step length and stride width variability; main effects of head orientation were found for all evaluated parameters and main effects of group were found for step length and its variability and local divergence exponents in all directions.
Significance: As expected, the older adults group showed less stable gait (higher local divergence exponent), the shortest step length and greater step length variability. However, contrary to expectation, the dancers were not more stable. The yaw condition was the most challenging for all groups and the down condition seemed to be least challenging.

1. Introduction

During gait, the human body exhibits inverted pendulum like characteristics, so that minor changes in body orientation with respect to the gravitational acceleration vector can cause destabilization. Gait stability has been defined as the ability to maintain a stable walking, defined as a walking pattern that does not lead to falls despite such perturbations [1–3]. Since intrinsic or environmental perturbations are always present, the neuromuscular system must counteract these perturbations to maintain a stable gait pattern.

To control upright posture, humans rely on multimodal integration of sensory information [4–6]. The vestibular system likely contributes to this control by monitoring body orientation with respect to gravity through detection of motion of the head-in-space [7]. During normal walking, we actively dissociate our head movement from trunk movement [8], and use a head-in-space stabilization strategy [9–11], presumably to provide a reliable reference for vestibular and visual information. In daily life, we frequently change head orientation, for instance when performing a visual search during walking, when preparing to cross a street, or when shopping to look for a product in the supermarket or the store windows. In addition, many dual tasks in daily life constrain head orientation, for example when we are speaking on the phone or reading from a screen while walking.

It has been reported that older adults exhibit lower head and pelvis accelerations than young adults [12] demonstrating differences in the way they control head motion to achieve head stabilization during locomotion [12–14]. Besides, aging of the vestibular system may impair the ability to detect changes in head acceleration [15]. This would suggest that gait stability in older adults may be differently affected by changes in head orientation than in young adults.

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Specific training may also affect the use of sensory information for balance control and hence the effect of head movement on gait stability. For example, dancers have been shown to differ from non-trained subjects in terms of sensory use for balance control [16]. Dance training imposes high balance demands while whole-body movements are synchronized to external events such as musical beats and visual cues [17]. Furthermore, dance training has been shown to cause changes in responses to vestibular input, such as suppressed nystagmus after repetitive stimuli, suppression of the vestibulo-ocular reflex, and an increased resistance to vertigo. These effects have been associated with structural brain adaptations [18–21]. This suggests that the gait stability in dancers might be less affected by changes in head orientation than in non-trained controls and that dance training could help to improve treatment for chronic dizziness.

A 6-months dance training was shown to increase local dynamic stability in older adults [22]. If interactions of head movement and orientation with age and dance training are confirmed, our results would indicate the potential of dance training to counter age-related problems to maintain gait stability with constrained head orientation or while moving the head.

The aim of this study was to compare the effects of different head orientations on gait stability between young adults, young adult dancers and older adults. Considering the motor and sensory deterioration associated with aging [23], we hypothesized that the older adults would be less stable and more affected by changes in head orientation. Since dancers have been shown to have better postural control compared to non-trained young subjects [24], we hypothesized that the dancers would present a better gait stability and would be less affected by changes in head orientation.

2. Methods

2.1. Subjects

Three groups of 10 participants were enrolled in the study: 1) 10 healthy and active young adults aged between 18 and 30 years (24.8 ± 2.39 years; 67.42 ± 16.05 kg; 1.71 ± 0.11 m (mean ± sd)) recruited from the university community; 2) 10 dancers, aged between 18 and 30 years (23.8 ± 3.19 years; 62.7 ± 13.87 kg; 1.68 ± 0.08 m), who engaged in regular high performance training of both ballet and other contemporary dance with an average experience of 7.2 ± 3.67 years and daily dance training of approximately 5 h per day, and 3) 10 community-dwelling older adults aged between 65 and 80 years (72.3 ± 6.9 years; 61.6 ± 6.95 kg; 1.59 ± 0.06 m) capable of understanding the instructions and data collection protocol (assessed by Mini-Mental State Examination (MMSE), minimum score of > 24 points). Neither the young nor the older adults had participated in regular dance classes. Exclusion criteria included injuries, surgery and diseases of the nervous, musculoskeletal, visual and vestibular systems and use of medications that can provoke dizziness as an adverse effect. The Ethics Committee for Human Research of the local university approved the experimental protocol, and all volunteers gave informed consented prior to participation.

2.2. Procedures

Kinematic data from reflective markers (heels, lateral malleoli, second and fifth metatarsal heads, and the spinous process of the tenth thoracic vertebrae, T10) were recorded using a 3D motion capture system with ten infrared cameras operating at 100 samples/s (Vicon Nexus, Oxford Metrics, Oxford, UK). Each participant walked on a level treadmill at preferred walking speed (PWS), estimated using a previously reported protocol [25] wearing their own regular shoes and a safety harness.

The participants performed four trials of 4 min each, with different head orientations (i: control; ii: dynamic yaw; iii: static up; iv: static down). For the "control" condition, participants kept their head in neutral orientation, for the dynamic "yaw" condition participants followed a led-light target moving horizontally at eye height, over 45° bilaterally at 117.13°/s (0.65 Hz), for the "up" condition participants were asked to maintain 15° of neck extension and for the "down" condition participants maintained a 40° neck flexion. To enforce head orientation for the last two conditions, the participants wore a laser pointer fixed on their head vertex and were instructed to point the laser beam to a target on the ceiling and on the ground, respectively.

2.3. Data analysis

Except for Lyapunov exponent calculation, the raw marker data were filtered using a low pass, zero-lag, fourth order Butterworth filter with a cutoff frequency of 6 Hz. Steps were detected as the zero-crossings of heel marker velocities in the anteroposterior direction. Step frequency (SF) was determined as the inverse of the average duration between two consecutive heel-strikes between limbs (i.e., left followed by right, or right followed by left). The average step length (SL) was calculated from the average treadmill speed and the average step frequency. Step width (SW) was determined as the mediolateral distance between the heels during heel strikes. Spatiotemporal parameter variability was calculated by the standard deviation over all steps in a trial.

The margins of stability (MOS) were calculated as distances between the extrapolated center of mass and the border of the base of support taken as the fifth metatarsal head marker of the leading foot for ML MOS, and the heel marker of the leading foot for AP MOS [26].

Local dynamic stability (LDS) was assessed by the Lyapunov exponent (LE), which was calculated using Rosenstein's algorithm [27]. The mediolateral (ML), anteroposterior (AP) and vertical (VT) T10 marker velocities were calculated via the three-points method [28]. Velocity time series were first resampled, using piecewise cubic hermite interpolating polynomials (pchip), so that each time series of 88 strides contained 8800 samples, adopting a normalization with a fixed number of strides and a fixed number of samples across all data [29]. Next, a state space was constructed, with a fixed time delay of 10 samples and number of embedding dimension of 5 for all directions [30]. The LE was calculated as the slope of the mean divergence curve, whose horizontal axis was normalized by stride from 0 to 0.5 stride [31].

2.4. Statistical analysis

As the data were normally distributed (Shapiro-Wilk test, $p > 0.05$), a mixed repeated measures ANOVA model was applied to assess the main effects of Group (three groups) and Condition (four head orientation conditions), as well as their interaction effects, followed by Tukey correction for post-hoc group comparisons. To compare PWS among groups, a one-way ANOVA was applied, followed by Tukey correction for post-hoc tests. All statistical analysis were performed with Jamovi software (version 0.9) using $p < 0.05$.

3. Results

The PWS differed between the groups ($F(2,27) = 6.26$; $p = 0.006$; $\eta^2 = 0.317$). The young adults walked significantly faster (1.33 ± 0.14 m/s) than the old adults (1.05 ± 0.12 m/s) ($p < 0.01$). The dancers showed PWS of 1.24 ± 0.24 m/s, which was not significantly different from the two other groups.

3.1. Spatiotemporal gait parameters and variability

The ANOVA results are presented in Table 1. For step length (Fig. 1A), there was significant main effect of Condition ($F(3,78) = 3.91$; $p = 0.01$; $\eta^2 = 0.129$) and Group ($F(2,26) = 14.5$; $p < 0.01$; $\eta^2 = 0.527$), but no significant interaction effect. On

Table 1
Statistical results for basic and stability gait parameters. The bold text represents the statistically significant outcomes ($p < 0.05$). SL: step length; SW: step width; var: variability; LE: Lyapunov exponent; MOS: margin of stability; ML: mediolateral; AP: anteroposterior; VT: vertical direction.

		SL	SW	SL var	SW var	LE ML	LE AP	LE VT	MOS ML	MOS AP
Condition	F (378)	3.91	6.86	12.39	41.94	23.84	7.32	9.39	8.53	7.87
	p	0.01	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
	η2	0.129	0.187	0.255	0.499	0.466	0.208	0.258	0.237	0.225
Group	F (226)	14.5	2.68	16.5	0.49	9.17	6.17	6.53	2.67	0.391
	p	< 0.01	0.087	< 0.001	0.618	< 0.001	0.006	0.005	0.088	0.680
	η2	0.527	0.171	0.559	0.036	0.413	0.322	0.334	0.170	0.029
Head Condition x Group	F(6,78)	0.235	1.93	5.12	8.06	0.644	0.970	0.514	0.706	0.541
	p	0.964	0.086	< 0.001	< 0.001	0.694	0.451	0.796	0.646	0.775
	η2	0.015	0.105	0.211	0.192	0.025	0.055	0.028	0.039	0.031

average, subjects walked with larger steps during the “control” condition than during the “up” condition ($p = 0.009$). The older adults adopted the smallest steps during all conditions compared to young adults ($p < 0.001$) and to dancers ($p = 0.001$). Step width (Fig. 1B) showed only a significant main effect of Condition ($F(3,78) = 6.86$; $p < 0.001$; $\eta^2 = 0.187$), where in the “yaw” condition participants demonstrated significantly wider steps compared to the “up” ($p = 0.009$) and “down” ($p < 0.001$) conditions.

Step length variability (Fig. 1C) showed significant main effects of Condition ($F(3,78) = 12.39$; $p < 0.001$; $\eta^2 = 0.255$), of Group ($F(2,26) = 16.5$; $p < 0.001$; $\eta^2 = 0.559$) and a Condition x Group interaction ($F(6,78) = 5.12$; $p < 0.001$; $\eta^2 = 0.211$). In the “yaw” condition participants presented higher step length variability compared to “control” ($p < 0.001$), “up” ($p = 0.014$) and “down” ($p < 0.001$) conditions. In the static “up” condition higher step length variability was observed compared to the “down” condition ($p = 0.033$). The older adults presented greater step length variability than the young adults and dancers ($p < 0.001$). Among the older adults, step length variability was greater in the “yaw” condition than in all other conditions ($p < 0.001$). Moreover, the older adults presented greater step length variability than the young adults and dancers in the “control” and “yaw” conditions ($p < 0.001$) and also for the “down” condition ($p = 0.041$) when compared to young adults.

Step width variability (Fig. 1D) showed a significant main effect of Condition ($F(3,78) = 41.94$; $p < 0.001$; $\eta^2 = 0.499$) and significant Condition x Group interaction effect ($F(6,78) = 8.06$; $p < 0.001$; $\eta^2 = 0.192$), but no main effect of Group. Post-hoc comparisons showed that step width variability was higher in the “yaw” condition compared to the other three conditions ($p < 0.001$). During the “yaw” condition, older adults showed greater variability than in other conditions ($p < 0.001$). The young adults showed higher step width variability in the “yaw” condition than in the “control” condition ($p = 0.02$).

3.2. Margins of stability

The ML margin of stability (Fig. 2A) showed only significant main effects of Condition ($F(3,78) = 8.53$; $p < 0.001$; $\eta^2 = 0.237$). In the “control” condition subjects had a significantly larger ML margin of stability than in the “up” ($p = 0.001$) and “down” ($p = 0.010$) conditions. Moreover, in the “yaw” condition participants had a larger ML margin of stability than in the “up” ($p = 0.001$) and “down” ($p = 0.009$) conditions.

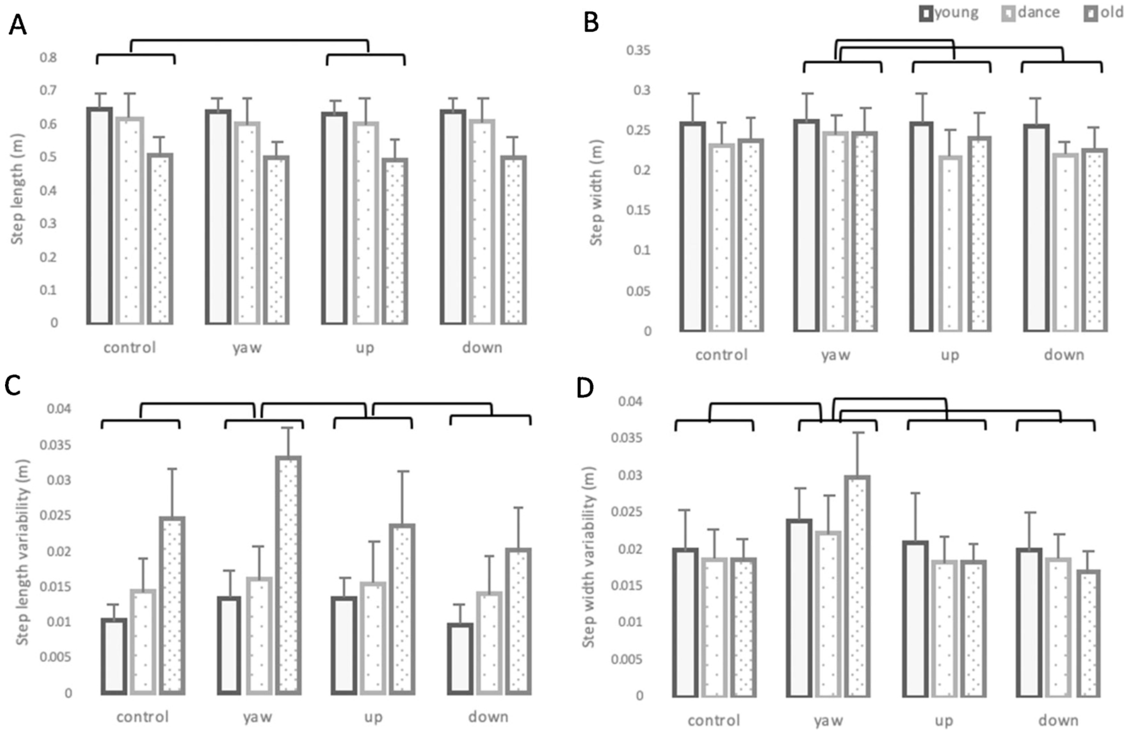

Fig. 1. Mean values and standard deviation for step length (A), step width (B), step length variability (C) and step width variability (D). Horizontal bars indicate significant post-hoc differences between conditions or groups: $p < 0.05$.

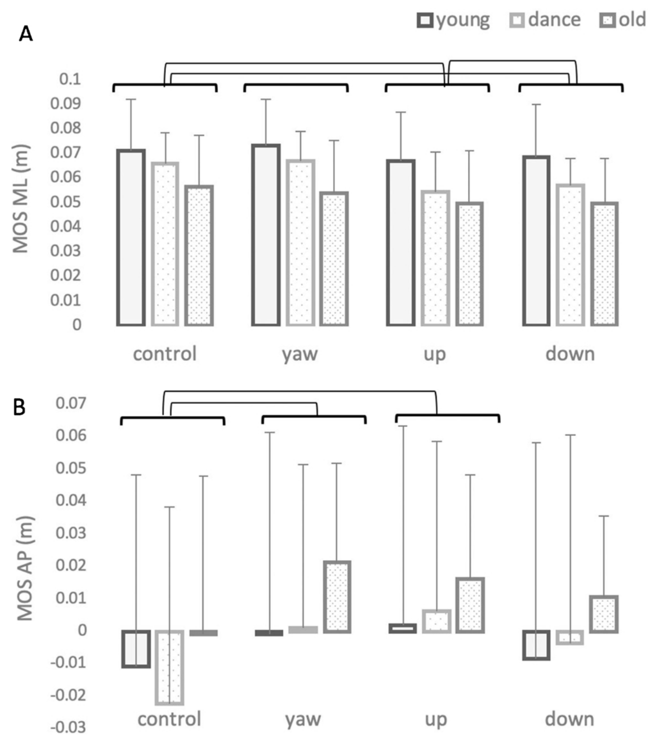

Fig. 2. Mean and standard deviation of margins of stability (MOS) in the mediolateral (ML) (A) and anteroposterior (AP) (B) directions. Horizontal bars indicate significant post-hoc differences between conditions: $p < 0.05$.

The AP margin of stability (Fig. 2B) was affected only by Condition ($F(3,78) = 7.87$; $p < 0.001$; $\eta^2 = 0.225$). In the “control” condition participants had a significantly lower AP margin of stability than in the “yaw” ($p = 0.001$) and “up” ($p < 0.001$) conditions.

3.3. Local dynamic stability (LDS)

For the ML−LE (Fig. 3A), significant main effects of Condition ($F(3,78) = 23.848$; $p < 0.001$, $\eta^2 = 0.466$) and of Group ($F(2,26) = 9.17$; $p < 0.001$, $\eta^2 = 0.413$) were found, but no Condition x Group interaction effect. Post-hoc tests showed that gait stability was lower (i.e. higher LE) during the “yaw” condition compared to the “control”, “down” and “up” conditions ($p < 0.001$), and the older adults had a lower stability (i.e. higher LE) than the young adults and dancers ($p = 0.003$).

Regarding to the AP−LE (Fig. 3B), significant main effects of Condition ($F(3,78) = 7.32$; $p < 0.001$, $\eta^2 = 0.208$) and Group ($F(2,26) = 6.17$; $p = 0.006$, $\eta^2 = 0.322$) were found, but no significant interaction effect. Post-hoc tests showed that gait stability was lower (i.e. higher LE) during the “yaw” condition than “down” condition ($p = 0.008$), while the “control” condition showed higher stability (i.e. lower LE values) compared to “yaw” ($p < 0.001$) and “up” ($p = 0.012$) conditions. The older adults had lower stability (i.e. higher LE) compared to the young adults ($p = 0.005$).

For the VT−LE (Fig. 3C) significant main effects of Condition ($F(3,78) = 9.39$; $p < 0.001$, $\eta^2 = 0.258$) and Group ($F(2,26) = 6.53$; $p = 0.005$, $\eta^2 = 0.334$) were found, but no significant interaction effect. The “yaw” condition had on average lower stability (i.e. higher LE) compared to “control” ($p = 0.001$), “up” ($p = 0.001$) and “down” ($p < 0.001$) conditions. The older adults presented the lowest stability (i.e. highest LE) and differed from both the young adults ($p = 0.013$) and dancers ($p = 0.011$).

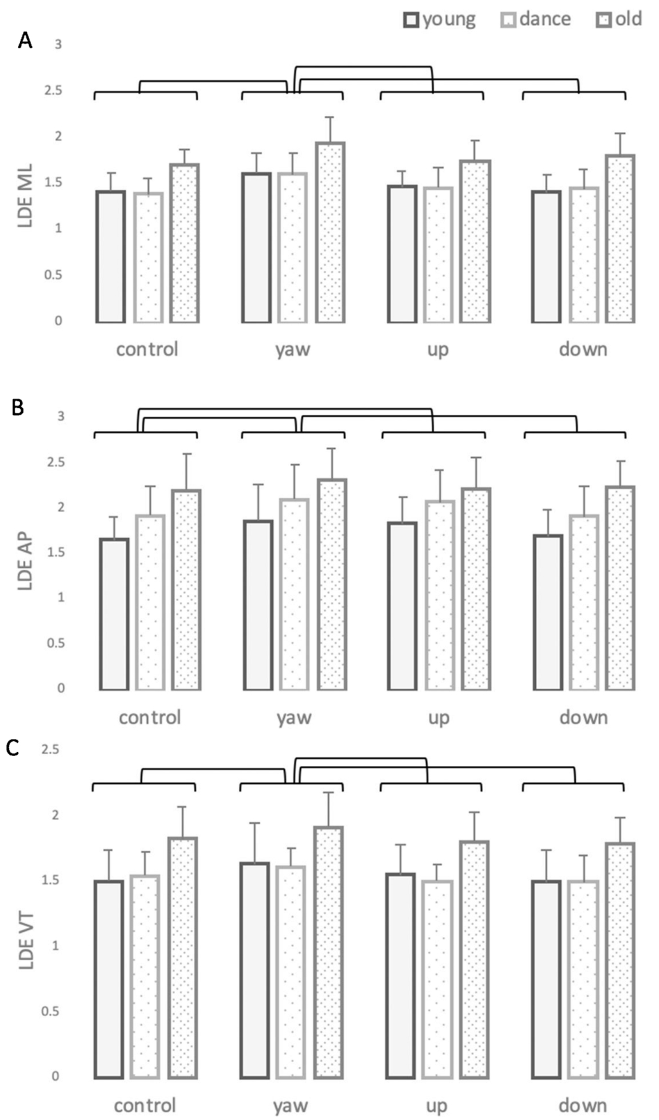

Fig. 3. Mean values and standard deviation of Lyapunov exponent (LE) in the mediolateral (ML) (A), anteroposterior (AP) (B) and vertical (VT) (C) directions. Horizontal bars indicate significant post-hoc differences between conditions: $p < 0.05$.

4. Discussion

The aim of this study was to compare the effects of different head orientations on gait stability between young adults, young dancers and older adults. The head orientation conditions and groups showed only small differences in gait characteristics analyzed. The older adults showed a less stable gait pattern and shorter steps than young adults and dancers. Surprisingly, the dancers were not more stable than the young adults.

As expected, the older adults evaluated in this study exhibited lower LDS, reduced step length and increased step length variability compared to young adults and dancers. In general, most of these adaptations are associated to reduced walking speed commonly adopted by older adults. Several studies showed that older adults decrease step length, increase step width and double support time [13,32,33]. Also, older adults showed greater gait variability of spatiotemporal kinematics and decreased LDS compared to young adults [34–38]. Aging of the vestibular system leads to a gradual decrease in density of the peripheral labyrinthine hair cell receptors number of vestibular receptor ganglion cells starting from the age of 30 years and the number of vestibular receptor ganglion cells begins to decrease by the age of 55–60 years [18,39,40], coinciding with a reduction in the ability to rapidly detect changes in head acceleration [15]. Although, these age-related changes of the vestibular system may contribute to the differences between the older adults' gait compared to young adults and dancers, the reduction of walking speed, step length and gait stability was observed irrespective of the changes in head orientation.

We expected the dancers to be the most stable and least affected by head orientation changes, but this was not confirmed in the current study. Dancing imposes high demands on executive and sensorimotor functions, including transferring visual and auditory information into motor action, and changes in the movements with respect to direction in space, speed, rhythm and amplitude [41,42]. Dance training-related plasticity mediating vestibular sensory processing showed distinct effects on perceptual and vestibular-ocular reflex responses, which may be explained by a generalized attenuation of vestibular signaling [20]. Therefore, the dynamical yaw condition was expected to cause less decrease in stability in dancers, but our experimental conditions did not cause differences in the way dancers and non-trained young adults maintained stability during walking. Although dancers presented better results than older adults, they presented comparable results to young adults and they were similarly sensitive to the "yaw" condition, presenting compromised stability compared to the other conditions. The stimulus velocity and frequency imposed by our dynamical condition may not have been high enough to differentially affect vestibular signal processing between groups, but do reflect every day scenarios.

Compared to the "control" condition, we observed that the head orientations studied reduced LDS and step length. Maintaining the head steady in space is a demand for the human neuromuscular system aiming to keep the visual field stable on the retina [11]. Simple slow head yaw can result in lateral center of mass displacements toward the contralateral side of the head movement [43], indicating that head orientation changes may cause degradation of dynamic postural control and gait stability, as found in our study in which the dynamic yaw motion showed the greatest impact on the gait parameters evaluated.

Our findings showed that in terms of local dynamic stability (LDS), the least stable condition (i.e. higher LE values) was the "yaw" condition, while the "down" condition was the most stable (i.e. lower LE values) in the mediolateral direction for the young adults, in the anteroposterior direction for the dancers and in the vertical direction for all three groups. In line with this, a study in which young and older adults walked overground with different head orientation changes, showed that walking with head yaw motion in both groups involved greater head, trunk and pelvis excursions than walking with head pitch motion (up and down) [44]. However, the margin of stability (MOS) in the mediolateral direction suggested that young adults and dancers were more stable (greater values) in the "yaw" condition. We suggest that this reflects a compensatory behavior to counteract the perturbing effects of the head yaw motion. During locomotion, eye rotations are generated to compensate for head movements, and these are vestibularly and visually mediated [45]. Several studies have investigated the effects of eye movements on postural control and pursuit eye movements increased associated body sway when constantly chasing a target in young adults [46,47], although saccadic eye movements have been shown to decrease postural sway [48]. This could be a contributing factor to the lower stability and the gait pattern adjustments seen during the "yaw" condition where participants were asked to pursuit a target, distinctly from the static head conditions (up and down).

In the "down" condition the young adults presented greater MOS values in the anteroposterior direction, as well as the longer steps. Looking down while walking is commonly used to identify lower limb trajectories and obstacles or surface irregularities in the walking path. The head down strategy seems to be more common in older adults although young adults also adopt this strategy with increasing walking speed [49]. Moreover, older adults adopt greater head flexion than young adults when walking overground [50]. Our findings suggest that the "down" condition increased LDS (i.e. lower LE) for young and dancer participants. Hence looking down possibly reflects a strategy to enhance gait stability.

Older adults presented lower gait stability and greater spatiotemporal variability than both young groups, as expected, but they were not more affected by changes in head orientation. Unexpectedly, no strong interaction effects of the group and head orientation were found (i.e. all groups responded similarly to all conditions, where the "yaw" condition was more detrimental with respect to gait stability and spatiotemporal parameters). Apparently, age-related reductions in the ability to detect changes in head orientation and in the integration of sensory information [7,15,51] did not enhance effects of constrained head orientation and head movement in the older group. Also, no differences were seen between young adults and dancers, while these are commonly seen in standing balance. We expected that enhanced sensory weighting and movement perception would have aided the dancers to be less affected by head orientation changes during locomotion. Dance training might improve vestibular sensory integration for posture and dynamical motion of the dance, but it seems not to improve stability while walking under the conditions tested.

Not measuring head kinematics was a limitation of this study, but compliance with task instructions was verified during the measurements. Eye motion tracking would have provided additional information with respect to visual responses. Regarding our study design, it would have been interesting to additionally measure a group of older dancers, to see if dance training could ameliorate some of the age-related effects on gait stability. However, current results do not suggest effects of dance training under the conditions tested. In conclusion, we found that head orientation affects gait stability and spatiotemporal parameters for all evaluated groups, specifically head yaw movement appeared to destabilize gait.

5. Conclusions

The different head orientations slightly affected the gait pattern of all groups, where the "yaw" condition was the most challenging and the "down" condition was the least challenging for gait stability. Older adults were less stable and adopted a smaller step length, but with greater variability,but they were similarly affected by changes in head orientation as young adults. Dancers did not show a more stable response to head orientations changes than young controls, suggesting that dance training did not lead to greater gait stability.

Declaration of Competing Interest

The authors have no conflict of interest to declare.

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