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Effect of age on postural performance and control strategies during changes in visual input and dual-tasking stances

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A R T I C L E I N F O

Keywords:
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Middle-aged
Multisensory reweighting
Muscle stiffness

A B S T R A C T

Background: With age, people begin to experience deterioration in standing balance, especially when sensory input is suddenly removed or added. Here, we sought to explore the effects of age on postural performance and postural control strategies.
Methods: The convenience sample consisted of 15 young, 10 middle-aged, and 14 elderly healthy adults. They were instructed to stand with their feet together in four randomly administered conditions involving visual input removal/addition and single-/dual-tasking. Dual-tasking involved continuous subtraction by 3s.
Results: Postural sway displacement in the two older groups seemed larger than that in the younger group; however, neither the main effect of group ($F_{2, 36} = 1.152$, $p = .327$) nor the group × time interaction effect ($F_{4, 27} = 0.229$, $p = .922$) was significant. Greater stiffness of the lower leg muscles was observed in the vision-addition condition than in the vision-removal condition in only the elderly group ($t_{13} = -2.755$, $p = .016$). The dual-tasking condition resulted in smaller sway displacement ($F_{1, 36} = 7.690$, $p = .009$) and greater muscle stiffness ($F_{1, 36} = 5.495$, $p = .025$). In the vision-removal condition, the increase in muscle stiffness due to dual-tasking was significantly larger in the middle-aged ($t_9 = -3.736$, $p = .005$) and elderly groups ($t_{13} = -2.512$, $p = .026$).
Conclusions: In healthy older individuals, age-related changes were observed in control strategies used to maintain standing balance upon changes in visual input. The dual-task paradigm induced the use of an ankle-stiffening strategy in middle-aged and elderly adults.

1. Introduction

After their fifth decade, humans start to experience deterioration in standing balance [1]. An individual's balance ability is maintained by a compound control system including motor, sensory, and cognitive functions [2–4]. During everyday sensory transitions, our nervous system must continuously change the prioritization of visual, vestibular, and somatosensory inputs to provide the

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most reliable information for postural stability; this process is termed “multisensory reweighting” [5]. The relative weight given to each sensory input depends on the availability, intensity, and resolution of the afferent signals [6].

Multisensory reweighting occurs when a visual input is removed or added. For example, when an individual enters a dark room, visual input is largely removed, and the relative sensory weight shifts toward the other two sources of information. Teasdale et al. [7] documented that elderly adults exhibited increased sway dispersion within 2–6 s after being asked to close their eyes compared to younger adults. The entire process of sensory adaptation may take up to 10 s [8]. When an individual leaves a dark room, visual input is suddenly added, and multisensory reweighting occurs again, with some relative sensory weight shifted back to the visual channel. Teasdale et al. [7] found that young adults rapidly adapted within 6 s after being asked to open their eyes, with reduced sway dispersion; in contrast, elderly adults still showed increased sway dispersion.

Although aging impacts multisensory reweighting both during sensory removal and addition, it remains unclear how postural control strategies change as a function of age. First, numerous studies have contributed to the understanding of postural control attention demands [9,10]. A typical paradigm in this line of research is the dual-task paradigm, in which postural control, considered the primary task, and a secondary task are performed at the same time. The dual-task paradigm may help to reveal changes in the capacity of attentional resources due to aging. Teasdale et al. [11] reported a more increased center of pressure velocity in elderly adults and a prolonged reaction time for the secondary task in both young and elderly adults after the addition of proprioceptive information. Their study, however, did not include a single-task condition and did not compare the changes of postural performance due to dual-tasking.

Second, if aging causes deterioration of the multisensory reweighting ability, does this deterioration lead to the adaptation of a different postural strategy in addition to deteriorations in postural performance? Assessing muscle stiffness may provide hints as to which postural strategy is adapted in different age groups. Muscle stiffness increases in a linear manner with contractile force and muscle activation [12–14]. It has been reported that muscle stiffness of the gastrocnemius medialis increases during quiet stance compared to a supine posture [15]. Research has also shown that elderly adults have a larger increase in muscle stiffness during quiet stance than young adults; this increase may compensate for age-related decreases in tendon stiffness [16,17], suggesting age-related influences on muscle contractions [18].

Determining the postural control strategies underlying deteriorations in postural performance during multisensory reweighting as a function of age would pave the way to promote health and prevent falls in elderly people. Hence, the purpose of this study was to explore the effects of age on postural control strategies and postural performance. To assess postural performance, postural sway was recorded in three age groups of adults (i.e., young, middle-aged, and elderly adults) before and after the removal/addition of visual input. To assess postural control strategies, the dual-task paradigm was adopted, and muscle stiffness of the gastrocnemius medialis was recorded. Our first hypothesis was that elderly adults, but not middle-aged adults, would have larger sway displacement than younger adults in the first 2–6 s after a change in visual input but not in the later stage (11–15 s). Our second hypothesis was that the dual-tasking condition (a concurrent backward-counting task) would result in greater sway displacement than the single-tasking condition; furthermore, we predicted that this effect would be more pronounced in middle-aged and elderly adults than young adults. Our third hypothesis was that middle-aged and elderly adults would exhibit a larger increase in muscle stiffness after a change in visual input than young adults.

2. Methods

2.1. Participants

Healthy adults were recruited for this study including fifteen young adults (age: 22.7 ± 2.9 years; seven women and eight men), ten middle-aged adults (50.6 ± 4.8 years; six women and four men), and fourteen elderly adults (64.2 ± 3.2 years; ten women and four men) (Table 1). Their mean years of education were 15.3 ± 1.4, 19.7 ± 2.5, and 14.8 ± 4.8 years, respectively. Their mean masses were 65.8 ± 12.2, 64.3 ± 12.8, and 64.3 ± 6.9 kg, respectively. Their mean heights were 166.7 ± 9.0, 164.6 ± 9.0, and 160.3 ± 5.0 cm, respectively. All participants were right-footed, with the exception of one elderly participant who was left-footed. The exclusion criteria were a Mini Cognitive Test (Mini-Cog) score <2 [19], any major neurological disorder, musculoskeletal trauma within the past three months, or the current use of medications that may affect balance. All participants provided written informed consent. The experimental procedures were approved by the Institutional Review Board of Chung Shan Medical University Hospital (CS2-19143) and were in accordance with the Declaration of Helsinki.

Table 1
Demographic characteristics of participants (mean ± standard deviation).

Characteristic	Young adults (n = 15)	Middle-aged adults (n = 10)	Elderly adults (n = 14)
Age (years)	22.7 ± 2.9	50.6 ± 4.8	64.2 ± 3.2
Sex (female/male)	7/8	6/4	10/4
Years of education	15.3 ± 1.4	19.7 ± 2.5	14.8 ± 4.8
Body mass (kg)	65.8 ± 12.2	64.3 ± 12.8	64.3 ± 6.9
Body height (cm)	166.7 ± 9.0	164.6 ± 9.0	160.3 ± 5.0

2.2. Postural tasks

The participants were told to avoid drinking caffeine or alcohol for 24 h prior to the experiment. In each 40-s trial, participants stood barefoot with their feet together, with each foot on a force platform (Bertec FP4550-08, USA) (Fig. 1). Each of the four conditions contained five trials; these conditions combined vision removal/addition and single/dual tasks and were administered in a random order. The participants were instructed to maintain their standing balance, stay relaxed, and look straight ahead. The removal/addition of visual information was achieved by means of electronically controlled shutter goggles (PLATO Visual Occlusion Spectacles; Translucent Technologies, Toronto, Ontario, Canada). In each trial, changes in visual status occurred at 17–22 s after the beginning of the trial; this interval was randomly selected for each condition and not revealed to the participants.

2.3. Cognitive task

The arithmetic task used in this study was selected given the findings of the systematic review by Al-Yahya et al.; mental tracking tasks appeared to exert greater interference regarding human balance than other types of cognitive tasks, such as reaction time tasks [20]. According to Fraizer and Mitra [21], a pure, single-tasking baseline condition is problematic because it lacks control over what participants think about, i.e., their attentional focus. Concerns stemming from the use of such uncontrolled baselines can be avoided by restricting performance comparisons to manipulations of task difficulty [21]. Therefore, we used an arithmetic task, counting backward by 1 from a randomly selected number between 70 and 99, as the baseline control condition (single-tasking). The true arithmetic task involved counting backward by 3 from a randomly selected number between 70 and 99 (dual-tasking).

2.4. Measurement of muscle stiffness

Stiffness indicates the ability of muscles to resist shape changes caused by an external force. Immediately after each trial began (pre) and within 2 s after (post) each change in visual status, muscle stiffness was manually measured by a hand-held MyotonPRO (Myoton AS, Tallinn, Estonia), which induces oscillation of the muscle tissue by a mechanical impact with a force up to 0.4 N. The most prominent point of the gastrocnemius medialis of the dominant leg was marked and used as the measurement point. The triplescan mode (3 continuous measurements from the same point, each for 1.5 m s) was used. The mean of these three scans were used for analyses.

2.5. Calculation of CoP sway amplitude

The ground reaction force was measured by the force platforms at 1200 Hz. The curves of the instantaneous center of pressure (CoP) position along the mediolateral axis in each trial were reduced to 21-s matrices encompassing 6 s before the change in visual status and 15 s afterward. The change in visual status corresponded to t = 0 s, and the changes in CoP were referenced to the same time point. The CoP position signal was bandpass filtered between 0.1 and 5 Hz. The average absolute CoP sway amplitude was calculated for each 1-s time window, and then averages were computed for the pre- (−6 to −2 s), post- (2–6 s), and prolonged (11–15 s) interval periods.

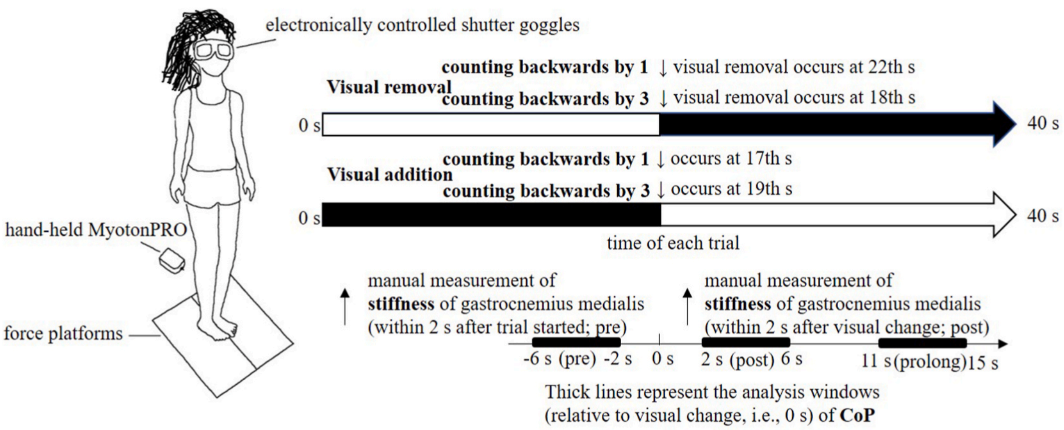

Fig. 1. Experimental procedure. Participants were asked to stand with their feet together during four conditions (random order) that combined vision removal/addition with single-/dual-tasking (continuous subtraction by 1 or 3, respectively). During each 40-s trial, visual information was removed or added after a randomly selected interval, ensuring that this change was unexpected, through electronically controlled shutter goggles. Center of pressure (CoP) data were collected via two force platforms, and based on the time of changes in visual status (set to 0 s), the following three time windows were established: pre- (−6 to −2 s), post- (2–6 s), and prolonged interval (11–15 s) periods. Muscle stiffness of the gastrocnemius medialis of the dominant leg was measured manually by a hand-held MyotonPRO and was based on the time of changes in visual status (set to 0 s); the following two time instances were established: the pre- (within 2 s after the trial start) and post-interval (within 2 s after changes in visual status) periods.

2.6. Statistical analyses

Data were analyzed using SPSS (14.0, SPSS Inc., Chicago, USA). The normality of all data was first assessed using the Kolmogorov–Smirnov test. If the data were not normally distributed, nonparametric tests were used for analysis. A repeated-measures analysis of variance (ANOVA) investigating CoP sway amplitude was performed with 3 groups (young, middle-aged and elderly) × 2 visual status (removal and addition) × 2 dual-tasking conditions (single and dual) × 3 time intervals (pre-, post-, and prolonged interval periods). A separate repeated-measures ANOVA investigating muscle stiffness was performed with 3 groups (young, middle-aged and elderly) × 2 visual status (removal and addition) × 2 dual-tasking conditions (single and dual) × 2 time intervals (pre- and post-interval periods). When a significant interaction effect was found, simple effect analyses were performed to isolate interaction effects by comparing differences between conditions in each group [22]. When a significant effect of time was found, preplanned simple contrasts were performed to compare intervals with the Pre interval (−6 to −2 s). The Greenhouse–Geisser correction was used for the degrees of freedom when violations of the sphericity assumption were detected. The significance level was set at $p < .05$.

3. Results

CoP sway amplitude. Fig. 2 and Table 2 show the sway amplitude of the CoP at three intervals (pre-, post- and prolonged interval periods) relative to changes in visual status. Overall, in the vision-removal condition, the sway amplitude increased in the pre-interval period and was maintained in the post-interval period. On the other hand, in the vision-addition condition, the sway amplitude decreased in the pre-interval period and was maintained in the post-interval period. The visual status × time interaction was significant ($F_{2, 72} = 8.208$, $p = .001$, $\eta_p^2 = 0.186$). Furthermore, fluctuations in CoP sway in the vision-removal condition were greater than those in the vision-addition condition. There was a significant main effect of visual status ($F_{1, 36} = 11.090$, $p = .002$, $\eta_p^2 = 0.236$).

Postural sway seemed larger in the middle-aged and elderly groups than that in the young group. However, in contrast to our first hypothesis, there was neither a significant main effect of group ($F_{2, 36} = 1.152$, $p = .327$) nor a significant group × time interaction ($F_{4, 27} = 0.229$, $p = .922$).

Furthermore, in contrast to our second hypothesis, the concurrent backward-counting task resulted in smaller sway displacement; in other words, there was a significant main effect of task ($F_{1, 36} = 7.690$, $p = .009$, $\eta_p^2 = 0.176$). There was also a significant group × time × dual-tasking interaction effect ($F_{4, 72} = 2.902$, $p = .028$, $\eta_p^2 = 0.139$). Preplanned simple contrasts, combining data from the vision-removal and vision-addition conditions, revealed significantly increased CoP sway from the pre-to post-interval periods but only in the single-tasking condition in the young group ($t_{14} = -2.263$, $p = .040$).

Muscle stiffness. Fig. 3 and Table 3 show the stiffness of the gastrocnemius medialis, which was recorded within 2 s after each trial started (pre-interval period) and after the change in visual status (post-interval period). There was a significant main effect of time ($F_{1, 36} = 5.891$, $p = .020$, $\eta_p^2 = 0.141$), with increases in muscle stiffness after changes in visual status. There was also a significant visual status × time interaction ($F_{1, 36} = 8.561$, $p = .006$, $\eta_p^2 = 0.192$), with increases in muscle stiffness occurring after changes in visual status in only the vision-removal condition ($t_{38} = -4.566$, $p < .001$).

In contrast to our third hypothesis, there was not a significant main effect of group ($F_{2, 36} = 0.333$, $p = .719$) or a significant group × time interaction ($F_{2, 36} = 0.101$, $p = .904$). However, as clearly shown in Fig. 2, greater muscle stiffness was observed in the vision-addition condition than in the vision-removal condition in only the elderly group ($t_{13} = -2.755$, $p = .016$); in other words, there was a significant visual status × group interaction ($F_{2, 36} = 7.182$, $p = .002$, $\eta_p^2 = 0.285$).

Fig. 2 shows that muscle stiffness was greater during the dual-tasking condition than the single-tasking condition, indicating a significant main effect of the dual-tasking condition ($F_{1, 36} = 5.495$, $p = .025$, $\eta_p^2 = 0.132$). There was a significant visual status × dual-

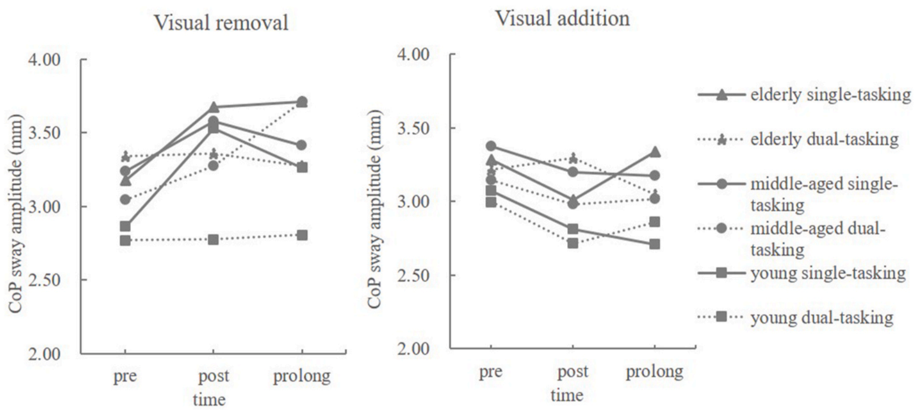

Fig. 2. Center of pressure (CoP) sway amplitude in the three age groups. The average absolute CoP sway amplitude was calculated in the mediolateral direction for the vision-removal (a) and vision-addition (b) conditions as well as the single-tasking (solid line) and dual-tasking (dotted line) conditions. Based on the time of changes in visual status (set to 0 s), the following three time windows were established: pre- (−6 to −2 s), post- (2–6 s), and prolonged interval (11–15 s) periods.

Table 2

Center of pressure (CoP) sway amplitude. The average absolute CoP sway amplitude was calculated in the mediolateral direction for the vision-removal and vision-addition conditions as well as for the single-tasking and dual-tasking conditions in the three age groups in the following three-time windows: pre- (−6 to −2 s), post- (2–6 s), and prolonged interval (11–15 s) periods relative to the change in visual status (set to 0 s).

	CoP sway amplitude, mm, mean ± SE	Visual removal			Visual addition		
		Pre	Post	Prolong	Pre	Post	Prolong
Young	single-tasking	2.86 ± 0.22	3.53 ± 0.26	3.26 ± 0.26	3.07 ± 0.21	2.81 ± 0.26	2.71 ± 0.25
	dual-tasking	2.77 ± 0.23	2.78 ± 0.26	2.81 ± 0.21	3.00 ± 0.23	2.72 ± 0.23	2.86 ± 0.23
Middle-aged	single-tasking	3.24 ± 0.27	3.58 ± 0.32	3.42 ± 0.32	3.37 ± 0.26	3.20 ± 0.32	3.17 ± 0.31
	dual-tasking	3.05 ± 0.28	3.27 ± 0.32	3.71 ± 0.26	3.15 ± 0.28	2.98 ± 0.28	3.02 ± 0.28
Elderly	single-tasking	3.18 ± 0.23	3.67 ± 0.27	3.71 ± 0.27	3.28 ± 0.22	3.01 ± 0.27	3.34 ± 0.26
	dual-tasking	3.34 ± 0.23	3.36 ± 0.27	3.28 ± 0.22	3.22 ± 0.23	3.29 ± 0.24	3.05 ± 0.24

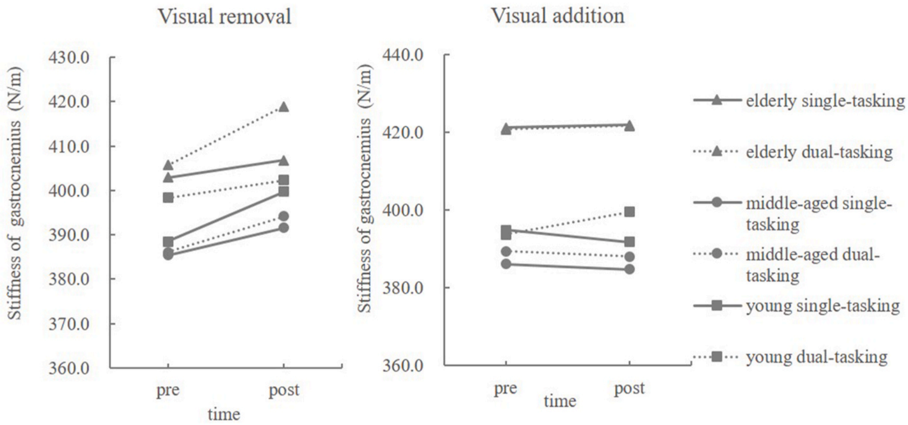

Fig. 3. Stiffness of the gastrocnemius medialis in the three age groups. The average triplescan values are shown for the vision-removal (a), vision-addition (b), single-tasking (solid line) and dual-tasking (dotted line) conditions. Based on the time of changes in visual status (set to 0 s), the following two time instances were established: pre- (within 2 s after the trial start) and post-interval (within 2 s after changes in visual status) periods.

Table 3

Stiffness of the gastrocnemius medialis. The gastrocnemius stiffness data are shown for the vision-removal, vision-addition, single-tasking and dual-tasking conditions in the three age groups in three time windows: (within 2 s after the trial start) and post-interval (within 2 s after changes in visual status) periods.

Gastrocnemius stiffness, N/m, mean ± SE		Visual removal		Visual addition	
		Pre	Post	Pre	Post
Young	single-tasking	388.5 ± 21.4	399.8 ± 21.9	394.9 ± 22.1	391.8 ± 21.1
	dual-tasking	398.3 ± 22.4	402.3 ± 22.5	393.7 ± 22.8	399.5 ± 21.7
Middle-aged	single-tasking	385.4 ± 26.2	391.6 ± 26.8	386.1 ± 27.1	384.8 ± 25.9
	dual-tasking	386.1 ± 27.4	394.2 ± 27.5	389.4 ± 28.0	388.1 ± 26.5
Elderly	single-tasking	402.9 ± 22.1	406.8 ± 22.7	421.3 ± 22.9	421.9 ± 21.9
	dual-tasking	405.7 ± 23.2	418.9 ± 23.2	420.8 ± 23.6	421.7 ± 22.4

tasking × time × group interaction ($F_{2,\ 36} = 5.445$, $p = .009$, $\eta_p^2 = 0.232$); this was followed by preplanned simple contrasts. In the vision-removal condition, there was a significantly smaller increase in muscle stiffness from the pre-to post-interval periods due to dual-tasking in the young group ($t_{14} = -3.874$, $p = .002$), and a significantly larger increase in muscle stiffness from the pre-to post-interval periods due to dual-tasking in the middle-aged group ($t_9 = -3.736$, $p = .005$) and elderly group ($t_{13} = -2.512$, $p = .026$).

4. Discussion

In contrast to our hypotheses and previous research [7], fluctuations in postural performance upon changes in visual information did not differ among young, middle-aged, and elderly adults. This lack of difference could stem from the relative youth and health of our elderly adults, who were free of major neurological disorders. Previous research has provided evidence that multisensory reweighting is particularly inefficient in fall-prone older adults compared with healthy older adults [5,23]. Although our results revealed no obvious age-induced impairment in postural performance when challenged with tasks necessitating multisensory reweighting, age-related changes in postural control strategies were evident.

We hypothesized that fluctuations in muscle stiffness due to changes in visual status would differ among young, middle-aged, and elderly adults. We found that elderly adults exhibited greater stiffness of the lower leg muscle in the vision-addition condition than in the vision-removal condition; this difference was not found in the young and middle-aged groups. In the vision-addition condition, trials began with occluded visual input. Our elderly participants did not exhibit an obvious decrease in postural performance compared to their younger counterparts; instead, they instantly increased their muscle stiffness and maintained this level of muscle stiffness throughout the trial even after vision was restored.

Previous research has shown that, accompanied by increased muscle stiffness in postural tasks, the electromyography activity of both the anterior and posterior sides of the lower leg muscles is increased in elderly adults [16]. Hence, an additional increase in muscle stiffness during challenging postural tasks in the elderly population may indicate the adoption of cocontraction of the lower leg muscles [24], known as the ankle-stiffening strategy [25]. The ankle-stiffening strategy aims to decrease postural sway by increasing joint stability [18,25–27] but is not as direction-specific as the ankle strategy [28]. Excessive cocontraction of muscles impedes adaptive reactions when the postural system is challenged during the performance of dynamic tasks [29]. Indeed, higher muscle cocontraction is particularly evident in elderly adults with worse postural performance [30–32].

We expected that dual-tasking (a concurrent backward-counting task) would have a larger impact on sway displacement than single-tasking and that this larger impact would be further magnified by age. In contrast, the concurrent backward-counting task resulted in smaller sway displacement. This decrease could be due to increased stiffness of the lower leg muscle, especially in the vision-removal condition in the middle-aged and elderly groups. Echoing our above explanation of the muscle cocontraction strategy, Dault et al. [33] proposed that a higher frequency of postural sway during dual-tasking is due to the postural control strategy of muscle cocontraction, which requires less attentional resources than reciprocal muscle contraction. Craig and Doumas [32] reported that it took elderly adults five times longer than young adults to perceive a change in proprioceptive information. Thus, the dual-tasking paradigm in the vision-removal condition revealed the reduced attentional capacity in the middle-aged and elderly adults, which then led to a necessary compensatory change in the postural control strategy.

There are two limitations of this study. First, stiffness was only measured for the gastrocnemius by a hand-held myotonometer. However, previous research measuring both muscle stiffness and electromyography activity has reported that when accompanied by increased muscle stiffness in postural tasks, the electromyography activity of both the anterior and posterior sides of the lower leg muscles is increased in elderly adults [16]. Second, our participants were relatively healthy adults; therefore, one must be cautious when generalizing our results to other older populations.

In conclusion, although healthy aging does not lead to obvious decreases in postural performance when challenged with tasks requiring multisensory reweighting, it is associated with different postural control strategies. Elderly adults increase the stiffness of the lower leg muscle when visual information is unavailable, indicating the use of an ankle-stiffening strategy. The dual-task paradigm induced the use of an ankle-stiffening strategy in both middle-aged and elderly adults, suggesting reduced attentional capacity and thereby compensation with the postural strategy. Our results have important real-life implications for everyday sensory transitions. If insufficient attentional resources are allocated to postural tasks in middle-aged and elderly populations, modification of sensory status may lead to an increased risk of accidental falls. Fall prevention programs should include dual-tasking training involving multisensory reweighting, especially for individuals 50 years of age or older.

Author contribution statement

Hui-Ya Chen, Chun-Ling Lin: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.
Han-Yu Chen, Shu-Zon Lou: Performed the experiments; Contributed reagents, materials, analysis tools or data.
Bing-Hong Chen: Performed the experiments.
Li-Yuan Chen: Analyzed and interpreted the data.

Data availability statement

Data will be made available on request.

Ethics statement

Declarations

The experimental procedures were approved by the Institutional Review Board of Chung Shan Medical University Hospital (CS2-19143) and were in accordance with the Declaration of Helsinki.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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