Full length article

Haptic information provided by anchors and the presence of cognitive tasks contribute separately to reducing postural sway in young adults

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A B S T R A C T

Background: Haptic information provided by the anchors reduces postural sway while standing upright. It is unclear whether this benefit would remain in the presence of cognitive tasks combined with a more challenging postural task.
Research question: Our aim was to investigate the effects of the anchors and visual and auditory cognitive tasks on postural control in young adults in a challenging balancing task.
Methods: Twenty young adults stood upright on a balance beam with the central portion of each foot placed over the beam and feet at shoulder width without and with the use of the anchors in three cognitive conditions: control, visual Stroop task, and auditory digit-monitoring task. Each anchor consisted of a flexible cable with a light load (125 g) attached at one end of the cable. With the anchors, the participants held the flexible cable in each hand with the light load resting on the ground while keeping tension in the cable.
Results: Both visual and auditory cognitive tasks reduced the center of pressure (COP) ellipse area, the root mean square of the margin of dynamic stability (based on the extrapolated center of mass, COM) and increased the COM time-to-contact relative to the boundaries of the base of support in the AP direction. The anchors reduced the COP ellipse area.
Significance: There is a functional integration between postural control and cognitive tasks, such that postural sway was reduced to facilitate the execution of the cognitive tasks. Anchors were effective in reducing postural sway, suggesting that haptic information was able to benefit postural control in a challenging balancing task regardless of the cognitive task.

1. Introduction

Postural sway can be adaptively modulated to facilitate the performance of other non-postural tasks [1–3], which is known as the functional integration hypothesis. This hypothesis is similar to the facilitation viewpoint put forward by Stoffregen et al. [4] and states that postural sway is reduced to allow the appropriate execution of other non-postural tasks (i.e., a supra-postural task such as a cognitively-demanding visual search task). Using light touch (LT) of the index finger on a rigid surface has been shown to reduce postural sway [2,5]. Chen et al. [2,5] used LT at the same time as a visual search task to test the functional integration hypothesis in young and older adults. They showed that, when performed simultaneously, the LT and visual task reduced postural sway and improved visual search accuracy in both age groups, supporting the functional integration hypothesis. We tested the

functional integration hypothesis in older adults with and without a history of falls using LT and haptic anchors [6]. Haptic anchors provide information about body orientation relative to the support surface and reduce postural sway. We found that the visual Stroop task and the haptic cues reduced postural sway in both older adult groups, also supporting the functional integration hypothesis.

Although these studies suggest the existence of synergy between posture and perceptual-cognitive tasks, one aspect to consider is the difficulty level of the postural task. Mauerberg-deCastro et al. [7,8] showed that young adults with and without intellectual disability used the anchors to reduce postural sway when standing on a balance beam. Oullier et al. [9] showed that even on a balance beam, young adults coupled their movement to the movement of a moving room, suggesting that the reduction in the support surface does not affect the interaction with the visual stimulus. It is unclear; however, whether individuals
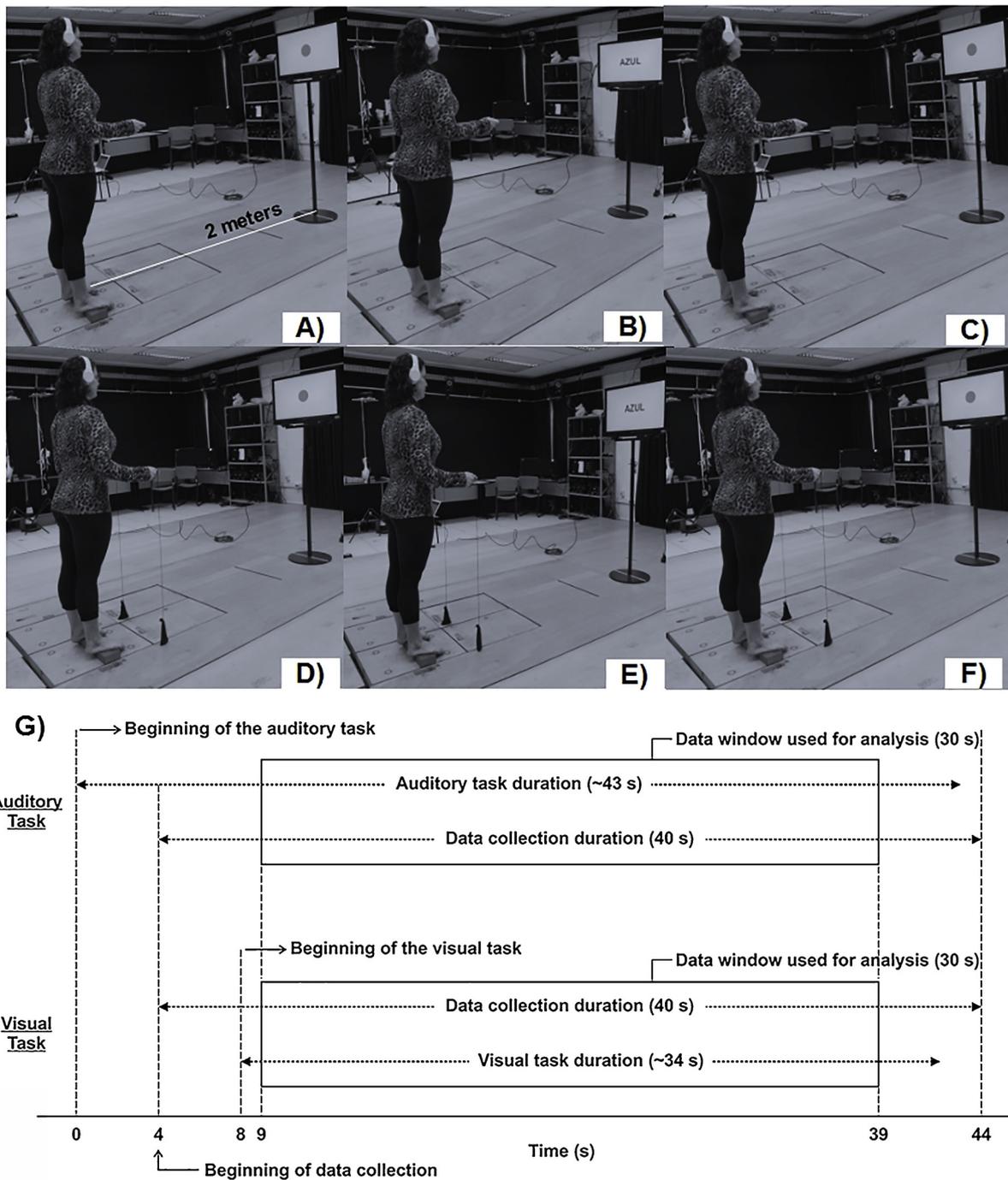
Fig. 1. Pictures of each of the experimental conditions: (A) without the anchors and without any cognitive task; (B) without the anchors and with the visual task; (C) without the anchors and with the auditory task; (D) with the anchors and without any cognitive task; (E) with the anchors and with the visual task; and (F) with the anchors and with the auditory task. (G) Timeline showing the beginning and end of both cognitive tasks relative to the beginning of data collection. The rectangle highlights the section used for data analysis.

would demonstrate functional integration by decreasing postural sway while standing in a challenging posture (i.e., on a balance beam) and performing a non-postural visual task in the presence of the haptic anchors.

Different studies have shown that an auditory task [10,11] can also diminish postural sway. It has been suggested that automaticity may explain the effect of the auditory task based on the idea that an auditory task shifts the focus of attention to the environment, which ensures an automatic and more efficient mode of postural control [10,12]. Prior studies comparing visual and auditory tasks have shown a greater reduction in postural sway with the use of visual compared to auditory

tasks [13,14]. The difference between sensory modalities is probably because the visual task demands an additional stable visual support of the surrounding scene to detect the necessary information [13,14]. A challenging balancing task has the potential to influence the difference between sensory modalities since a reduced base of support can be destabilizing enough to impair the execution of the cognitive tasks. When standing on a balance beam, an increase in postural sway has the potential to initiate a fall and the need to step off the beam to recover balance [8]. If this occurs, the individual will stop performing the cognitive task. Thus, to prevent this from happening postural sway reduction should be similar between sensory modalities when standing
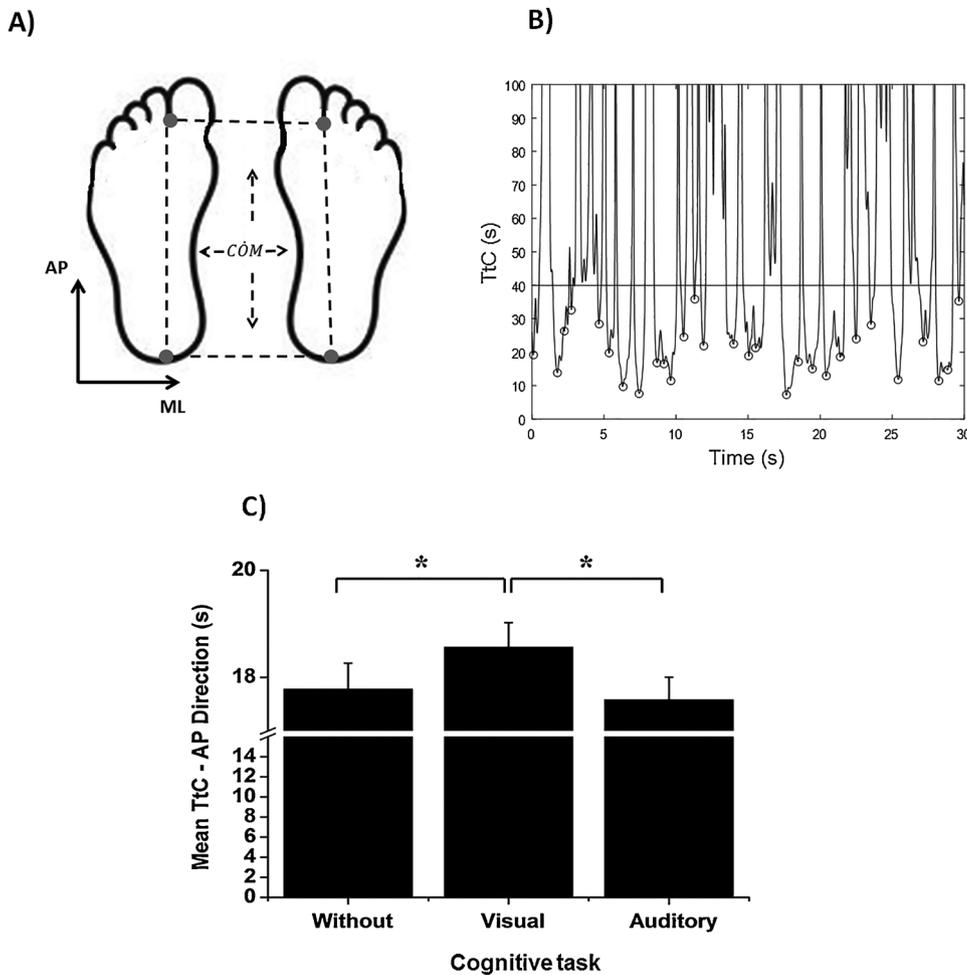
A)

B)

C)

Fig. 2. (A) Illustration of the direction of the COM vector velocity (arrows with dashed lines) used to calculate the margin of dynamic stability (MDS) and time-to-contact (TtC) in both AP and ML directions. Dotted lines connecting the markers on the feet indicate anterior, posterior, dominant and non-dominant boundaries of the base of support (BOS). The mean value of the AP coordinate of the marker located on the right and left 2nd metatarsal head defined the anterior margin, while the mean value of the AP coordinate of the right and left heel defined the posterior margin of the BOS. The mean value of the ML coordinate of the metatarsal and heel markers of each foot defined the dominant and non-dominant margin of the BOS. (B) Time-series of the TtC showing the local minima (circles below 40 s) used to determine the mean TtC. (C) Mean and standard error of the mean for the TtC in the AP direction in each of the cognitive tasks. * indicates significant differences between cognitive tasks.

on the balance beam.

This study aimed to investigate the combined effect of anchors and both visual and auditory cognitive tasks on postural control of young adults in a challenging balancing task. Besides measuring typical center of pressure (COP) parameters to quantify postural sway (e.g., ellipse area), we quantified the relationship between movement of the center of mass (COM) and the boundaries of the base of support (BOS) using the margin of dynamic stability [15] (COM/BOS relationship according to position) and time-to-contact [16] (COM/BOS relationship according to time). We used these last two parameters because the visual and auditory tasks can impact head movement, which in turn may influence COM displacement. We expected that both the anchors and cognitive tasks would decrease postural sway in young adults. The former because of the haptic input and the latter because of the functional integration hypothesis. In addition, we did not expect to find differences in postural sway between visual and auditory tasks because of the challenging balancing task.

2. Methods

2.1. Participants

Twenty healthy young adults (10 male; 24.0 ± 3.0 years; 1.71 ± 0.08 m; 74.6 ± 14.1 kg) participated in this study. They had normal visual acuity [17] and were physically active (9.3 ± 1.0) according to the Baecke questionnaire [18,19]. The local ethics committee approved all the procedures.

2.2. Procedures

Participants stood upright on a wood balance beam (width 40 cm, length 10 cm, height 4 cm) positioned on the force plate (Bertec 4060-NC, Columbus, EUA) with feet shoulder-width apart. The central portion of each foot was placed over the beam, such that the feet extended over the front and back of the beam. Thirty-nine markers were placed on specific anatomical landmarks, based on the *Plug-in-Gait Full Body* model, and were tracked by an 8-camera motion analysis system (MX-T40S, Vicon, Oxford, UK). These signals were digitally synchronized and collected at 100 Hz.

Participants performed three trials of each of the six experimental conditions combining the anchors and the two cognitive tasks (Fig. 1A-F) with data collection lasting 40 s. Participants were not instructed to prioritize any of the tasks during data collection. In the anchor conditions, participants maintained their arms with the elbow flexed at approximately 90° while holding the cable with the load (125 g) resting on the ground. Participants held the cables in front of them. They pulled the cables just enough to keep them taut without removing the loads from the ground [20]. Participants stood 2 m away from a flat screen TV (29″) adjusted to their eye height. An orange target on a white background (circle with an 11.5-cm diameter) was projected for all trials except in the visual task. The visual task consisted of the adapted Stroop color-word test [21], with 40 words displayed one at a time at intervals varying between 600–1000 ms. The written color names could be congruent ("BLUE" displayed in blue text) or incongruent ("BLUE" displayed in red text). Participants mentally counted the number of congruent displays in each trial. The auditory task was the digit-monitoring task [22] where 22 random numbers between 1 and 9 were
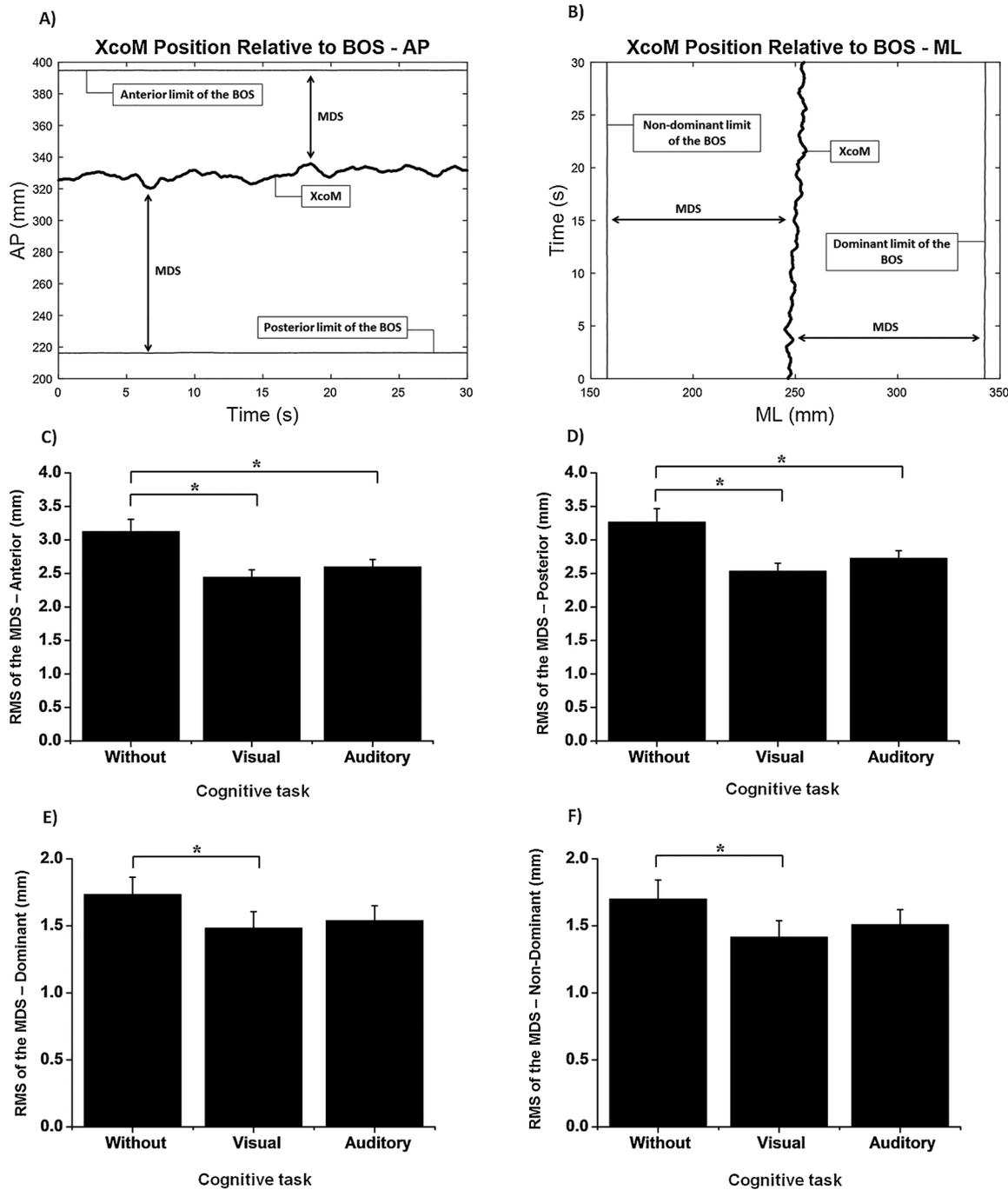
Fig. 3. Time-series of the extrapolated center of mass position (XcoM, represented by the thickest line) relative to limits of the base of support (BOS, represented by the thinnest lines), in AP (A) and ML (B) directions. Arrows indicate the distance of the margin of dynamic stability (MDS) in relation to anterior and posterior (AP) and dominant and non-dominant (ML) limits of the BOS. Mean and standard error of the mean for the root mean square (RMS) of the MDS relative to the anterior (C), posterior (D), dominant (E) and non-dominant (F) boundaries of the BOS for each cognitive task. * indicates significant differences between cognitive tasks.

presented via headphones at intervals varying between 500–1000 ms. Before each trial, three target numbers were provided, and participants were asked to mentally count the number of times they heard those target numbers. At the end of each trial, in both cognitive tasks, participants informed the result of their mental counting. Before data collection, participants performed each of the cognitive tasks in a seated position to familiarize themselves with the requirements of these tasks. The duration of the auditory and visual tasks was ~43 s and ~34 s, respectively. Data collection started ~4 s after the beginning of the auditory task and ~4 s before the beginning of the visual task. Even after finishing the cognitive task, the participants continued in the

postural task until the end of the 40 s period (Fig. 1G).

2.3. Data analysis

The first and the last 5 s of each trial were discarded leading to 30 s of each standing trial. This removal guaranteed that the data analyzed corresponded to a period of time when the participant was performing the cognitive task (Fig. 1G). We digitally filtered the three-dimensional coordinates of the individual markers using a low-pass 4th-order Butterworth filter with a 6-Hz cut-off frequency. These markers defined a 15-body segment model to compute the COM using the anthropometric

Table 1

Statistical results for main and interaction effects of the MANOVA and the follow-up univariates for the time-to-contact (TtC) in both anterior-posterior (AP) and medial-lateral (ML) directions, root mean square (RMS) of the margin of dynamic stability (MDS) relative to all four boundaries of the base of support (anterior, posterior, dominant, and non-dominant), and head movement in AP, ML and vertical directions. The ANOVA results for the ellipse area are also shown.

Variables	Haptic contact	Cognitive task	Haptic contact * Cognitive task
MANOVA - Mean TtC *Follow-up univariate*	Wilks' λ = 0.729, $F_{2,18}$ = 3.343, p = 0.058	Wilks' λ = 0.722, $F_{4,74}$ = 3.276, p = 0.016	Wilks' λ = 0.917, $F_{4,74}$ = 0.817, p = 0.515
AP direction	$F_{1,19}$ = 3.994, p = 0.060	$F_{2,38}$ = 5.057, p = 0.011	$F_{2,38}$ = 1.500, p = 0.236
ML direction	$F_{1,19}$ = 3.422, p = 0.080	$F_{2,38}$ = 2.816, p = 0.072	$F_{2,38}$ = 0.065, p = 0.938
MANOVA - RMS of the MDS *Follow-up univariate*	Wilks' λ = 0.757, $F_{4,16}$ = 1.283, p = 0.318	Wilks' λ = 0.520, $F_{8,70}$ = 3.383, p = 0.002	Wilks' λ = 0.834, $F_{8,70}$ = 0.829, p = 0.580
Anterior boundary	$F_{1,19}$ = 1.550, p = 0.228	$F_{2,38}$ = 15.109, p $\leq$ 0.0001	$F_{2,38}$ = 0.173, p = 0.842
Posterior boundary	$F_{1,19}$ = 1.965, p = 0.177	$F_{2,38}$ = 12.901, p $\leq$ 0.0001	$F_{2,38}$ = 2.249, p = 0.119
Dominant boundary	$F_{1,19}$ = 2.508, p = 0.130	$F_{2,38}$ = 5.601, p = 0.007	$F_{2,38}$ = 0.051, p = 0.951
Non-dominant boundary	$F_{1,19}$ = 1.303, p = 0.268	$F_{2,38}$ = 6.261, p = 0.004	$F_{2,38}$ = 0.036, p = 0.965
MANOVA - Head Movement *Follow-up univariate*	Wilks' λ = 0.848, $F_{3,17}$ = 1.017, p = 0.410	Wilks' λ = 0.574, $F_{6,72}$ = 3.836, p = 0.002	Wilks' λ = 0.857, $F_{6,72}$ = 0.964, p = 0.456
AP direction	$F_{1,19}$ = 2.688, p = 0.118	$F_{2,38}$ = 10.939, p $\leq$ 0.0001	$F_{2,38}$ = 0.690, p = 0.508
ML direction	$F_{1,19}$ = 1.812, p = 0.194	$F_{2,38}$ = 7.577, p = 0.002	$F_{2,38}$ = 0.297, p = 0.745
Vertical direction	$F_{1,19}$ = 1.119, p = 0.303	$F_{2,38}$ = 3.943, p = 0.028	$F_{2,38}$ = 1.234, p = 0.303
ANOVA - Ellipse Area	$F_{1,19}$ = 11.324, p = 0.003	$F_{2,38}$ = 11.892, p $\leq$ 0.0001	$F_{2,38}$ = 0.770, p = 0.470

parameters described by Winter [23]. COM velocity corresponded to the first derivative of the COM position (central difference procedure).

We calculated time-to-contact (TtC) over the entire duration of each trial in the AP and ML directions as follows (Fig. 2) [16]: $TtC = (BOS - COM)/\dot{COM}$, where BOS represents the limit of the base of support, COM is the actual position of the COM, $\dot{COM}$ is the actual velocity of the COM. We defined the limits of the BOS based on the metatarsal head and heel markers of both feet (Fig. 2). The direction of the COM velocity vector defined the BOS boundary used to compute the TtC (Fig. 2). For instance, when the COM velocity vector pointed to the anterior boundary, we used that boundary to compute the TtC. Based on Haddad et al. [24], we identified the local minima of the TtC time series considering the threshold of 40 s (Fig. 2) and then calculated their mean.

For the margin of dynamic stability (MDS), we first calculated the extrapolated COM (XcoM) position [15]: $XcoM = COM + (\dot{COM}/\omega_0)$, where COM is the actual position of the COM, $\dot{COM}$ is the COM velocity and $\omega_0 = \sqrt{g/l}$, where g is the acceleration due to gravity and l is the COM height in relation to the ankle joint. MDS corresponds to the distance between the XcoM position and the limits of the BOS (Fig. 3 A,B). MDS was calculated over the entire duration of each trial in both AP and ML directions. A positive value for MDS indicates that the XcoM is located within the limits of BOS and the system is dynamically stable. The BOS boundary used to compute the MDS was also dependent on the direction of the COM velocity vector. We then computed the amplitude of the MDS in relation to each boundary of the BOS as the root mean square (RMS), after eliminating any trend in signal and setting it around zero. In the ML direction, we computed the MDS for the dominant and non-dominant sides, based on self-report of the participants to the question of which foot they would use to kick a ball.

We also analyzed head movement by defining the midpoint of the four markers placed on the head. The head movement amplitude was computed as the root mean square (RMS) of the midpoint in the AP, ML and vertical directions after eliminating any trend in the signal by setting it around zero.

The coordinates of the COP were obtained based on the forces and moments of force measured by the force plate. These coordinates were digitally filtered by a low-pass, 4th order, Butterworth filter with a cutoff frequency of 5 Hz [25]. An ellipse containing 95% of the data was adjusted over the COP displacement using the principal component analysis, and the area of this ellipse was calculated.

For the cognitive tasks, we computed the absolute error for each trial and summed up these errors across conditions for each participant.

2.4. Statistical analysis

For all variables, the mean of the three trials was used in the statistical analyses. We carried out two-way MANOVAs (haptic contact [with and without] x cognitive task [without, visual and auditory]) with repeated measures for both factors for the following set of dependent variables: 1) mean AP and ML TtC; 2) RMS of MDS relative to all four boundaries of the BOS; and 3) RMS of head movement in AP, ML, and vertical directions. Univariate analyses followed each MANOVA. For the ellipse area, we performed a two-way ANOVA (haptic contact x cognitive task) with repeated measures for both factors. Post-hoc tests with Bonferroni adjustments were performed whenever necessary. For the absolute error in the cognitive task, a Wilcoxon test was used to compare the haptic anchor conditions separately in the visual and auditory tasks. The significance level was set at p $\leq$ 0.05.

3. Results

Detailed statistical results are available in Table 1.

3.1. TtC

The MANOVA identified a main effect of cognitive task (p = 0.016), and the univariate tests showed this effect only in the AP direction (p = 0.011). The presence of the visual task increased the TtC compared to both the auditory task (p = 0.039) and the control condition (p = 0.043, Fig. 2C).

3.2. RMS of the MDS

The MANOVA showed a main effect of cognitive task (p = 0.002) and the univariate tests identified this effect in all boundaries of the BOS (p < 0.0001). For the anterior and posterior boundaries, the presence of both the visual (p = 0.001) and auditory (p < 0.01) tasks reduced the RMS of the MDS (Fig. 3C,D). For the dominant and non-dominant boundaries of the BOS, only the visual task reduced the RMS of the MDS (p < 0.009, Fig. 3E,F).

3.3. RMS of the head movement

The MANOVA showed a main effect of the cognitive task (p = 0.002) and the univariate analyses exhibited this effect in the AP (p $\leq$ 0.0001), ML (p = 0.002) and vertical directions (p = 0.028). Both
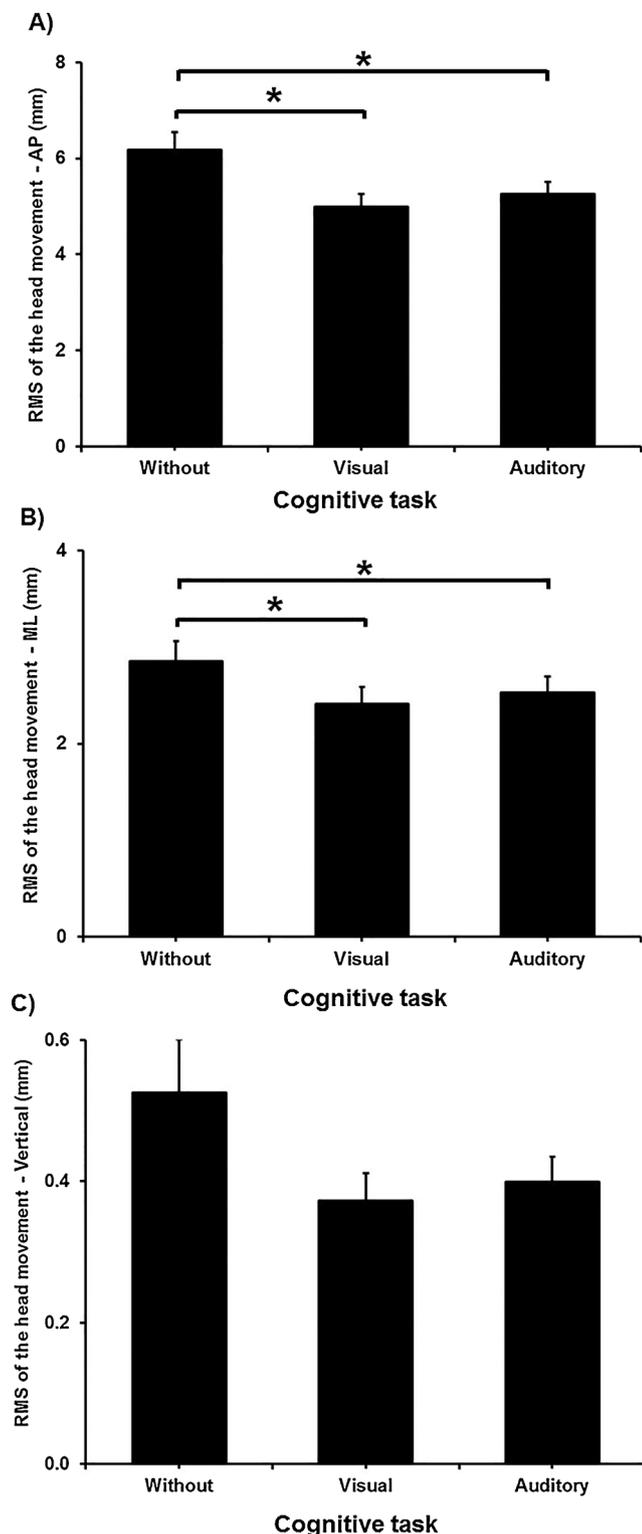
Fig. 4. Mean and standard error of the mean for the root mean square (RMS) of the head movement for each cognitive condition in the AP (A), ML (B), and vertical (C) directions. * indicates significant differences between cognitive tasks.

visual and auditory tasks reduced head RMS in the AP and ML directions (p < 0.04, Fig. 4). Post-hoc tests failed to identify differences in the vertical direction.

3.4. Ellipse area

The ANOVA showed main effects of the haptic contact (p = 0.003) and cognitive task (p < 0.0001). The anchors reduced the ellipse area (p = 0.003, Fig. 5A). Similarly, both visual (p = 0.001) and auditory (p = 0.003) tasks reduced the ellipse area (Fig. 5B).

3.5. Absolute errors in the cognitive tasks

The Wilcoxon test did not show a significant difference between haptic contact conditions in the visual (with: 1.3 ± 1.4 │ without: 1.4 ± 1.2 │ p = 0.883) and auditory (with: 3.2 ± 2.5 │ without: 2.3 ± 2.1 │ p = 0.253) tasks.

4. Discussion

We analyzed the combined effect of the anchors and the cognitive tasks on postural control in a challenging balancing task. Both the anchors and the cognitive tasks decreased postural sway independently, and there was no difference between visual and auditory tasks over postural sway, except for time-to-contact. The use of the anchors did not influence the performance on the cognitive task.

4.1. Independently, the anchors and the cognitive tasks reduced postural sway

Regardless of the presence and modality of the cognitive task, the haptic information provided by the anchors reduced the ellipse area on a challenging balancing task, which is consistent with prior studies [8,20,26]. When standing with the anchors, changes in body orientation relative to the ground alter the tension applied on the cables of the anchors, which is detected in hand tactile receptors [20]. In this way, the anchors provide haptic information about postural orientation relative to the ground that is used to minimize postural sway.

Both cognitive tasks reduced postural sway as well as head sway, and this effect was independent of the anchors, similar to previous research that used a LT paradigm [2]. The reduction in postural sway resulted in a steady head position on space thereby facilitating the gathering of visual and auditory information in both cognitive tasks. According to prior studies [2,27], our results indicate that the postural sway can be reduced to facilitate the performance of non-postural tasks such as the visual and auditory tasks. Moreover, the challenging balancing task resulted in a similar reduction in postural sway for both visual and auditory cognitive tasks. As suggested, the participants may have reduced body sway on the balance beam similarly in both cognitive tasks to ensure they could perform the cognitive task without interruption. Any destabilizing movement would result in stepping off the beam, which in turn would interrupt the execution of the cognitive task. In this case, a reduction in postural sway is necessary, regardless of the modality of the cognitive task, to guarantee the performance of the cognitive tasks. It is important to note; however, that the visual task led to a longer time-to-contact than the auditory task. This result supports previous findings [13,14] where the visual task demanded an additional stable visual platform.

4.2. The use of the anchors did not influence the performance on the cognitive tasks

Despite the reduction in postural sway with the anchors, their use did not affect the performance in the cognitive task. This finding partially agrees with Chen et al.'s findings [2] who observed reductions in postural sway with haptic information by LT, but the LT improved the visual search task performance, which was not the case with the anchors. According to one interpretation of the functional integration hypothesis [2], the anchors, as well as the LT, should improve performance in the cognitive task. The lack of improvement may be due to the
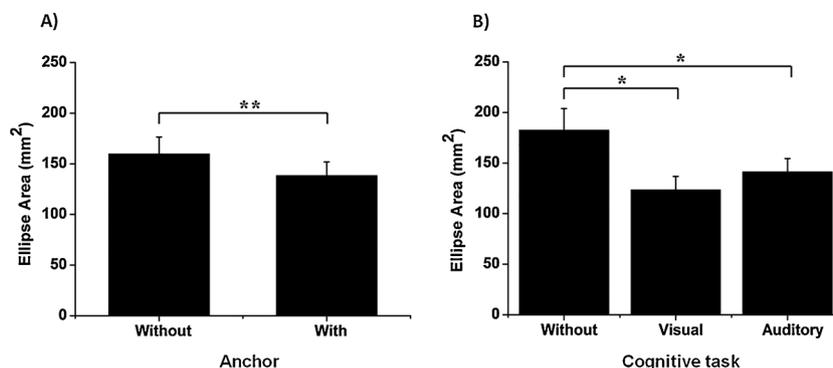
Fig. 5. Mean and standard error of the mean for the ellipse area for each anchor condition (A) and for each cognitive task (B). * indicates significant differences between cognitive tasks. ** indicates significant differences between anchors conditions.

differences in the demands of the LT and anchor task since the anchors involve the control of more degrees-of-freedom to keep the cable taut than does the LT [26]. One may also argue that the cognitive demand of the visual search task [2] is larger than the visual Stroop task used in the present study and; therefore, individuals could take more advantage of the body stabilization provided by the haptic input to identify the repeated letter while lightly touching a rigid surface than with the anchors. This possibility suggests that the effect of the decrease in postural sway from haptic input would be more evident with more difficult visual tasks.

4.3. Limitations

The size of the BOS in the AP direction used to compute some variables is larger than the actual BOS. Conversely, the size of the BOS in the ML direction was smaller than the actual BOS. These methodological differences artificially modified the functional boundaries, which overestimates the time-to-contact and margin of dynamic stability variables. Despite this, we believe it does not change the meaning of our findings since the analysis was focused on the differences between conditions. Another limitation could be the lack of a control condition without the balance beam. Although this condition could provide a direct test for the influence of the different modalities on postural sway reduction, the previous studies show a clear difference [13,14]. We opted to reduce the number of conditions to minimize the effects of fatigue and pain in the foot because standing on the balance beam may be uncomfortable.

5. Conclusion

Regardless of the cognitive task, the anchors were effective in reducing postural sway. Even with increased difficulty in the balancing task, functional integration resulted in reduced postural sway to facilitate the performance of the cognitive task, and this effect was similar for both sensory modalities. The ability to functionally modulate postural sway to achieve the goal of the non-postural tasks is preserved even in more challenging postural situations.

Acknowledgements

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