Postural Perturbations Induced by a Moving Virtual Environment Are Reduced in Persons With Brain Injury When Gripping a Mobile Object

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Background and Purpose: Gripping a mobile (unfixed) object increases standing postural stability in healthy individuals. We tested whether the same strategy is effective for stabilizing upright posture perturbed by a moving environment (virtual perturbation) in participants with traumatic brain injury (TBI).

Methods: Fifteen participants with mild-to-moderate postural deficits after TBI and a comparison group of 15 age-matched healthy subjects participated in the study. Participants stood for 1 minute in front of a large screen with a projected three-dimensional image of a boat; for 30 seconds the boat remained stationary (no visual stimulation condition), and for 30 seconds the boat rocked on the water at a speed of 15°/s (visual stimulation condition). The visual stimulation was applied in pseudorandom order (during either the first or second half of the 1-minute trial). To analyze postural stability, the displacement and velocity of the center of mass in the sagittal and frontal planes were compared between groups and across 4 experimental conditions, including standing with/without visual stimulation and with/without gripping a 300-g object (short wooden stick) in the dominant hand.

Results: Participants with TBI showed greater instability under all experimental conditions. The visual stimulation significantly increased postural oscillations in the sagittal plane by 35% to 63% across groups. Gripping a stick significantly reduced the stimulation-induced instability in the sagittal plane by 19% to 29%, although not to the level of the no-stimulation condition in either group.

Conclusion: The stabilizing effect of gripping an external object was confirmed. A possibility of using this effect as a balance aid strategy requires further investigation.

Audio Abstract available (see Audio, Supplemental Digital Content 1, http://links.lww.com/JNPT/A68 for more insights from the authors).

Key words: light touch, postural control, virtual perturbation, virtual reality, TBI

INTRODUCTION

Postural instability is a common and devastating consequence of traumatic brain injury (TBI), which includes an inability to maintain static upright posture, disequilibrium while walking, and inadequate postural adjustments to internal or external perturbations.1-6 Impairment of postural stability is particularly evident in visually crowded environments (ie, places with a large number of moving objects).7,8 These posture-related deficits increase the risk of falling and the associated secondary trauma.9,10 Considering that TBI survivors constitute one of the largest groups of people with disability worldwide,11 investigations of potentially destabilizing conditions and strategies for reducing postural instability are important in the context of rehabilitation.

To minimize instability in challenging situations while standing or walking, individuals with postural deficits frequently employ a strategy of lightly touching a stable supporting surface. Additional hand contact generates signals related to the direction, amplitude, and velocity of postural displacements, and provides a spatial frame of reference. When integrated into a common postural control scheme, this information contributes to the activation of appropriate muscles to reduce postural instability.12-14 The effect of light touch on postural stabilization has been demonstrated in numerous studies involving older healthy individuals15 and participants with stroke16 or vestibular dysfunctions.17 However, the light touch strategy is less useful in places where a stationary support is unavailable.

Recent studies involving neurologically intact, healthy individuals confirm that gripping an external object has a beneficial effect on the stability of upright posture. Regardless of the level of contact forces applied, holding the object in the hand reduces postural sway when standing with eyes closed or when perturbed by viewing a moving visual scene (visual perturbation).8,10 Similarly, postural stability is increased by gripping a load cell between the index finger and the thumb when standing on a rocker board20 or during a single-leg stance.21 Thus, there are many circumstances wherein gripping an external mobile object provides an additional gain in stability. Although the particular mechanisms...
underlying this effect have yet to be elucidated, the effect may be attributed to mutually beneficial interactions between postural and suprapostural tasks. Suprapostural task may include any voluntary movement or cognitive task, performed while standing.

The central nervous system controls both postural and suprapostural tasks as a single functional unit, which minimizes postural oscillations to improve the performance of the suprapostural task. For example, the postural sway is reduced in participants when standing and holding a tray with an unstable object or when performing a precision-aiming task. This functional interaction between 2 motor tasks is observed in healthy individuals, but it is unclear whether the same interactions remain intact after a brain injury. Studies report the decrease of postural stability in participants with acquired brain injury when they perform a secondary cognitive task. To perform postural and suprapostural tasks simultaneously, the neural system shares the allocated resources between both tasks. Because the neural resources are already limited and central response selection is slowed by brain damage, the deteriorated performance of the cognitive and/or postural tasks is observed.

The purpose of this study was to investigate the effects of gripping an external object (a light, short wooden stick) on postural stability in individuals with TBI-related postural and coordination deficits. Gripping an object in the hand was chosen as a typical motor task, representing a variety of activities of daily living. It requires less cognitive effort than dual-task activities (eg, calculating numbers or memorizing words) and thereby can affect postural stability differently. Both experimental paradigms used in this study have previously been tested in healthy individuals and participants with stroke. We anticipated that in individuals with brain injury postural stability would be increased by gripping the stick, as was demonstrated earlier in healthy individuals. If effective, the strategy could be used potentially in destabilizing situations and in places where stationary support surfaces are unavailable. These studies may yield information that is important for development of strategies to aid balance and postural stability in persons with TBI.

METHODS

Subjects

Study participants were 15 individuals with TBI (9 females; mean age ± standard deviation, SD, 35.3 ± 11.8 years), and a comparison group of 15 healthy sex- and age-matched participants (8 females; mean age ± SD, 33.4 ± 9.1 years) without known neurological, orthopedic, or cognitive deficits. Participants in both groups were matched in terms of height, with a mean height ± SD of 167 ± 5.8 cm in the TBI group, and 169 ± 5.3 cm in the control group. To ensure the best match, participants with TBI were recruited first, and then a group of healthy participants with similar height (± 3 cm), age (±3 years), and sex (±2 subjects of different sex in a group) was recruited. Eleven participants in the TBI group and 14 participants in the comparison group were right-handed, according to a self-report on the arm preference during the performance of fine motor daily life activities. All participants signed an informed consent form that was prepared in compliance with the Declaration of Helsinki and approved by the Institutional Review Board.

Participants with TBI were recruited from local rehabilitation centers. A recruitment letter was sent to physical therapists for distribution among potential participants. The letter explained experimental procedures and eligibility criteria, and asked potential participants to contact the investigator, if they were interested in participating in the study. The eligibility criteria included were as follows: (1) TBI sustained more than 6 months previously with a stable clinical status, (2) ability to stand unsupported for at least 2 minutes, (3) full or nearly full range of motion in major body joints, (4) normal or corrected to normal vision, (5) TBI-related mild-to-moderate ataxia involving upper and lower extremities, (6) postural instability, and (7) ability to follow simple instructions. The ataxia was indicated as hypo- or hypermetric extremity movements and lack of coordination during the performance of the nose-to-finger or heel-to-shin tests. Postural instability was indicated as excessive body oscillations while standing in the Romberg position (ie, standing with feet together, arms outstretched forward, and eyes closed). Screening for eligibility was performed by physical therapists. Those physical therapists had more than 5 years of experience working with patients with TBI.

Participants in the TBI group were evaluated by experienced physical therapists, with a battery of clinical tests before experiment began. The Ataxia test was used to rate ataxia of gait, stance, upper and lower extremities, intention tremor, and dysarthria according to a 6-point scale, with 0 points indicating no symptoms and 5 points indicating the most severe symptom manifestations in each testing category. A total score of 1 to 7 points corresponds to mild ataxia, 8 to 21 points to moderate ataxia, and 22 to 35 points to severe ataxia, with a score of more than 30 points indicating a total inability to perform any of the tested activities. The Berg balance scale was used to assess postural stability, with a score of 45 points or less indicating an increased fall risk. Gait performance was evaluated with the functional gait assessment (FGA). A score of 22 points or less on the FGA indicates an increased fall risk.

The visual perceptual abilities of participants were evaluated with a series of neuropsychological tests. Visual perception ability was evaluated with the motor-free visual perception test. This test measures visual discrimination, visual memory, visual spatial relations, and visual motor integration on the scale ranging from 55 to 145 points, with a score of 100 ± 15 points indicating average performance. The test is recognized by neuropsychologists as the most sensitive test to detect mild perceptual deficits. The Rey-Osterreith complex figure test (wherein participants were shown a card with a figure and instructed to duplicate the figure on a piece of paper) was used to assess visuococonstructive abilities. Scoring is based on the quality of 18 components of the copied figure. Scores for each component range from 0 (no credit) to 2 (full credit), with the best possible score being 36 points. Nonverbal visual memory was assessed with the visual reproduction test, which provides scaled scores ranging from 1 to 19 points.
Equipment and Experimental Procedure

Postural stability was measured as subjects stood in front of an 82-inch screen (1080p Mitsubishi DLP TV bundle, RealD Beverly Hills, CA). As illustrated in Figure 1, a computer-generated image of a boat slowly rocking on the water was projected on the screen in a three-dimensional format and viewed by the participant in the first-person view via shutter glasses (RealD Professional CrystalEyes 5). The virtual environment was developed by using WorldViz software (WorldViz LLC, Santa Barbara, CA), with computer graphics performed with Alias’ Maya package for 3D animation (Maya, Version 7.0.1; Autodesk, Inc, San Rafael). Once developed, the environment was streamed with a system that consisted of a PC (Intel Core 2 Duo Processor, Palo Alto) with a graphics accelerator (nVidia GeoForce Go 7300, Santa Clara).

Participants stood for 1 minute with both arms at their sides and feet a comfortable distance apart. For 30 seconds the boat remained stationary, and for 30 seconds the boat moved around its lateral axis in a sinusoidal up-and-down pattern (pitch) at a speed of approximately 15°/s, providing the visual stimulation intended to produce a virtual perturbation (see Supplemental Digital Content, http://links.lww.com/JNPT/A68). In pseudorandom order, the visual stimulation was applied during either the first or second half of the trial. Beginning from the initial horizontal position, the boat was displaced 30° up, 60° down past the horizontal, and back up to the horizontal. The full cycle of the boat movement was repeated 3 times, with an interval of 2 seconds during a 30-second period. To reinforce the illusion of movement, the water in the scene flowed at a realistic speed (as determined by the researchers).

Participants were instructed to stand quietly and focus on the moving part of the scene (eg, the railing of the boat as opposed to the stationary horizon—postural task). In randomly assigned trials, they were given a small object (stick) to lightly grip in the dominant hand (suprapostural task). The stick was a 300-g short custom-made wooden rod (length, 20 cm; height, 2.5 cm; width, 2.5 cm), described previously.19 The grip force applied to the stick was not monitored, as we previously showed that the level of contact forces does not affect the postural sway in healthy participants.19 A similar reaction was observed during test trials in participants with TBI, gripping the stick with less than 1, 5, and 10N of force.

Participants performed 10 trials in total. Five of the experimental trials began with the stationary boat (no visual stimulation), and the other 5 trials began with the moving boat (visual stimulation). Of 5 trials in each category with stimulus or no stimulus, 2 to 3 trials were performed holding the stick (stick), and in the remaining 2 or 3 trials participants stood without a stick (no stick). The order of all trials was randomized, and slight variation in the number of the stick versus no stick trials between participants unlikely impacted results.

Data Collection and Analysis

During task performance, kinematic data were collected by an optical motion analysis system (Qualisys AB, Gothenburg, Sweden), with data captured 100 Hz from 28 infrared markers placed on the major bony landmarks. An initial computation of the center of mass (COM) was done by using the average COM of all body segments, calculated with anthropomorphic tables. By using the linear displacements, the amplitude and velocity peaks of the COM in the sagittal and frontal planes were computed and analyzed. The amplitude was calculated as the peak-to-peak displacement of the COM in a given plane. The total experimental time of each trial (1 minute) was split into two 30-second parts (“no stimulus” and “stimulus” parts), and each part was analyzed separately.

To analyze the timing and direction of the postural responses to the visual stimulus, the trajectory of the COM in the sagittal plane was plotted against the boat trajectory, and the cross-correlation was applied. A negative cross-correlation coefficient was interpreted as movement of the measured parameters in opposite directions (ie, the subject swayed backward when the boat rocked down). A positive coefficient indicated displacement in the same direction. Mean coefficients between −0.25 and 0.25 indicated no relationship between the stimulus and COM response, with a coefficient either from 0.5 to 1, or from −0.5 to −1 indicating moderate-to-strong coupling between parameters.

The extent to which the effect of gripping the stick was dependent on the baseline level of postural stability was determined by correlation analysis. The amplitude and the velocity of the COM at baseline (ie, in the no-stick condition) were correlated to the amount of stability gain (COMgain) as a result of gripping the stick. The stability gain (%) was calculated with the following equation:

\[
\text{COM}_{\text{gain}} = \frac{\text{COM}_{\text{stick}} - \text{COM}_{\text{no stick}}}{\text{COM}_{\text{no stick}}} \times 100\%
\]

The normality of the data distribution was verified with the Kolmogorov-Smirnov test \((P > 0.5)\). Mixed 2-way analysis of variance with Tukey’s HSD (honest significant difference) test was used to compare the COM velocity, amplitude, and cross-correlation coefficients with the factors of group (TBI, comparison) and experimental conditions (stimulus, no stimulus, stick, no stick). The stability gain was analyzed with Pearson correlation coefficients. All statistical analyses were calculated with a significance level of \(\alpha < 0.05\).
RESULTS

Participants in the TBI group presented with different severities of postinjury impairments and functional limitations. Clinical scores and demographic information are presented in Table 1. Participants presented with the Ataxia test scores ranged from 3 to 19 points (mean, 7.2 ± 4.2 points). The participant scores ranged from 39 to 56 points (mean, 48.7 ± 5.1 points) on the Berg balance scale, and from 8 to 29 points (mean, 20.4 ± 6.1 points) on the FGA tests.

Nine of the participants in the TBI group had decreased visual perceptual abilities. In this group, the mean score on the motor-free visual perception test was 84.2 ± 8.75 points (range, 55-140 points). The mean score on the Rey-Osterreith complex figure test was 27.79 ± 8.75 points (range, 2-34 points); 10 participants demonstrated scores that were lower than or equal to the first percentile, indicating impairments in visuoconstructive abilities. The mean score on the visual reproduction test was 6.35 ± 4.01 points (range, 1-14 points), which indicates that their average visual memory abilities were in the low average range of function.

Overall, participants in the TBI groups exhibited greater postural oscillations than participants in the comparison group. The amplitude and velocity of the COM sway for the TBI and comparison groups under 4 different conditions is shown in Figure 2. Regardless of the experimental condition, compared with healthy participants, participants with TBI swayed with greater amplitude in the sagittal (F1,112 = 156.21; P < 0.001) and frontal planes (F1,112 = 37.34; P < 0.001). Compared with the healthy group, COM oscillations in the TBI group were characterized by significantly greater velocity in the sagittal (F1,112 = 4.58; P < 0.041) and frontal planes (F1,112 = 4.07; P = 0.053). Significant differences in the sagittal amplitude of the COM displacement were found between conditions (F3,112 = 19.45; P < 0.001; Figure 2A).

Table 1 illustrates the trajectories of the COM sway in the sagittal plane of one representative subject from the TBI group (top) and one subject from the comparison group (bottom). In both cases the visual stimulation was applied during the second half of the trial (30-60 seconds). In both participants, the amplitude of the COM sway was increased after a visual stimulation began (Figure 3), but was decreased when a stick was held in the hand. Similar responses were observed in all participants. On average, the application of a visual stimulus increased the sagittal amplitude by 63% in the TBI group (mean ± SD from 29.5 ± 16.2 mm to 48.1 ± 20.2 mm; P = 0.003) and by 58% in the comparison group (15.2 ± 5.2 mm to 24.1 ± 9.3 mm; P = 0.001). Gripping the stick during the visual stimulation significantly reduced the sagittal amplitude by 29% in the TBI group (to 34.1 ± 16.5 mm; P = 0.032) and by 21% in the comparison group (to 19.0 ± 7.8 mm; P = 0.024).

The velocity of the COM in the sagittal plane exhibited characteristics similar to those of sway, with significant differences between conditions (F3,112 = 15.50; P < 0.001; Figure 2B). The visual stimulation increased the velocity by 42% in the TBI group (mean ± SD, 17.8 ± 12.3 mm/s to 25.7 ± 15.3 mm/s; P = 0.001) and by 35% in the comparison group (9.5 ± 7.1 mm/s to 12.8 ± 4.1 mm/s; P = 0.004). Gripping the stick reduced the velocity in both groups when a visual stimulation was applied, by 25% in the TBI group (to 19.2 ± 11.2 mm/s; P = 0.049) and by 19% in the comparison group (to 10.4 ± 4.9 mm/s; P = 0.035). Some reductions in the COM oscillations with the stick grip were observed while standing without visual stimulation in both groups. The stick grip reduced the COM velocity (P = 0.036 for TBI; P = 0.047 for comparison), but did not change the COM amplitude (P = 0.085 for TBI; P = 0.094 for comparison).

Frontal plane postural oscillations were less responsive to the visual stimulation and stick grip conditions than were oscillations in the sagittal plane. No significant difference in the COM amplitude was observed between experimental conditions (F3,112 = 4.76; P = 0.059). Although the visual

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Table 1. Demographic Information and Clinical and Neuropsychological Test Scores for Participants With TBI

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Mean ± SD 6.6 ± 4.3 35.3 ± 11.8 7.2 ± 4.2 48.7 ± 5.1 20.4 ± 6.1 84.2 ± 26.1 27.7 ± 8.75 6.35 ± 4.01

*The Ataxia test by Klockgether.4

Abbreviations: BBS, Berg balance score35; FGA, functional gait assessment test36; MVPT, motor-free visual perception test37; ROCF, Rey-Osterreith complex figure39; SD, standard deviation; TBI, traumatic brain injury; VR, visual reproduction test.4
Figure 2. Averaged means (M ± SD) of the COM sagittal and frontal displacements and velocities in participants with TBI (black bars) and control individuals (open bars) during experimental conditions with or without the visual stimulus and stick. *Significant difference (P < 0.05) between experimental conditions.

The results of cross-correlation analysis (to quantify the relationship between sagittal displacements of the COM and the visual stimulation signal) showed that the cross-correlation coefficients were widely distributed. In the TBI and comparison groups, the maximum peak distribution was in the interval of −0.50 to −0.85 in all conditions (range, ±0.25 to ±1; Figure 4). When standing without the stick, participants with TBI moved in the direction of the visual stimulus in 35% of trials (with r range, from 0.5 to 1; Figure 4), swayed in the opposite direction in 46% of trials (with r range, from −0.5 to −1). Holding the stick did not change this relationship significantly with 29% and 47% of trials characterized by moving in the same and opposite directions, respectively. Participants in the comparison group swayed in the direction of the visual stimulation in 24% of trials and in the opposite direction in 43% of trials when standing without the stick, and in 27%
and 45% of trials of the same versus opposite direction when holding the stick. The direction and degree of sway did not change with repeated trials.

The extent to which the stick grip effect depended on the baseline level of postural oscillations was determined by Pearson correlation analysis. The amplitude and the velocity of the COM in the baseline (no stick) condition were correlated with the stability gain while gripping the stick. Correlation analysis was conducted for the sagittal COM oscillations only because changes in the frontal plane were less prominent.

The results of correlation analysis for the displacement and velocity of the COM sway during standing, with or without visual stimulation, are illustrated in Figure 5. In this figure, positive (or negative) mean values for the stability gain indicate a decrease (or increase) in the COM sway while gripping the stick, corresponding to an improvement (or deterioration) of postural stability. For each parameter, negative mean values for the stability gain were observed, mainly in participants who demonstrated high postural stability at baseline. As the baseline stability reduced, participants in both groups showed greater reductions in postural sway (stability gain) because of the stick grip. A moderate correlation was achieved, with coefficients ranging from $r = 0.51$ to $0.64$ ($P < 0.05$).

DISCUSSION

As expected, participants with TBI showed greater instability than healthy participants under all experimental conditions. The visual stimulation increased postural oscillations in the sagittal plane by 35% to 63% in all participants. However, these oscillations were not strongly related to the direction of the stimulus. The use of the stick grip reduced the stimulus-induced postural sway by 19% to 29%, although the baseline level of stability (no visual stimulation) was not reached in either group. The amount of stability gained under the stick grip condition moderately depended on the baseline stability level. In both groups, the stimulus- and grip-related changes in postural sway were less prominent in the frontal plane than in the sagittal plane.

Previous reports have documented a perturbation effect of visual field motions. A moving visual field generates the illusion of self-motion, triggering postural responses that perturb body stability. The magnitude of postural responses highly depends on characteristics of the moving visual field, such as its structure, location (peripheral vs central), the velocity, and frequency of oscillations. Therefore, a virtual perturbation effect of the visual stimulation is not always guaranteed. In this study, intensity of the visual stimulation seems to have been adequate to destabilize our TBI and healthy participants.

Typically, the direction of visually induced postural responses tends to align with the direction of visual stimulus motion. In our study, such a relationship was not obvious because 27% to 35% of the same-direction versus 43% to 47% of the opposite-direction body-boat coupling occurred in both
groups. The variability of these postural responses in our participants might have resulted from the nature of the virtual environment used for the visual stimulation. First, the latency of the postural response to visual stimulus may vary from 2 to 10 seconds. This suggests that a postural response from our participants to the visual stimulus of the boat movement may have occurred near the middle or end of the boat’s movement cycle, when the boat had already begun to change the direction.

Second, one part of the scene (represented by the boat itself) was moving, whereas the other part (represented by the horizon) was stable. In this case both parts of the scene could be perceived as moving in opposite directions relative to each other. Although our participants were instructed to focus their gaze on the boat railing, there was no guarantee they followed this instruction completely. Thus, it is possible that participants may have adjusted their upright position relative to the horizon line, perceived as moving away from the boat.

Third, postural adjustments may occur according to the subjective perception of the self-motion and body’s vertical position on the deck. As the deck began moving up or downward, a participant shifted in the opposite direction to prevent an imaginary fall. These possibilities are consistent with the findings of Fushiki et al., who showed that postural responses to observations of virtual scenes moving up and downward may vary from the same to opposite direction, depending on the direction of the visual stimulus. All these explanations are rather speculative and require further investigation.

In terms of the effect of the stick grip on postural stability in participants with TBI, some relevant empirical facts and potential mechanisms should be discussed. Numerous studies of healthy and neurologically impaired individuals have reported postural stabilization with different types of additional hand contacts. Greater effects were achieved when the participant contacted a stationary surface. The 2 mechanisms most frequently proposed as potential contributors to postural stability in these instances are deformation of mechanoreceptors at the point of contact (which provide information about the direction, amplitude, and velocity of the body displacements), and provision of an origin for the spatially referent frame to a freely oscillating body. Neither of these mechanisms seemed to be triggered by the mobile support in our study. This observation suggests that other physiological interactions might be responsible for the postural stabilization attained by gripping a stick.

Gripping an object in the hand introduces a secondary motor (suprapostural) task to the task of postural stability. The
impact of a suprapostural task on postural stability is not always predictable; it varies depending on the nature and priority given to the task and the neural resources available.\textsuperscript{22,27,30,49,50} In healthy individuals, the performance of a suprapostural task generally reduces body oscillations if the decreased movement benefits performance. For example, participants are more successful at holding a tray with an object imitating a glass of water and at precision-aiming with a laser pointer when they minimize their postural oscillations.\textsuperscript{24-26} Postural oscillations are also reduced during the performance of simple nonsense memory tasks.\textsuperscript{51} Experimentally, healthy participants even show reduced postural sway when asked to focus on holding a pole while standing.\textsuperscript{52} The explanation for these findings probably lies within the functional integration hypothesis.\textsuperscript{22,23} This hypothesis suggests that the central nervous system controls both postural and suprapostural tasks as a single coherent unit, thereby facilitating rather than deteriorating postural control. Alternatively, a conscious focus on movement control may constrain or “freeze” some degrees of freedom, making the body more rigid.\textsuperscript{53}

The beneficial effect of suprapostural tasks on postural control observed in healthy individuals may not be similarly beneficial in individuals with TBI, because brain injury essentially limits the available neural resources to produce sufficient postural and motor control. Even relatively simple tasks (eg, maintenance of an upright stance) may require additional attention after higher demands are placed on the central and executive mechanisms of the brain. At present there are limited experimental data describing the effect of a motor suprapostural task on postural stability in participants with TBI. Most experimental studies of suprapostural task performance in persons with acquired brain injury have used cognitive secondary tasks and reported their negative effects on postural control.\textsuperscript{54} However, with some exceptions.\textsuperscript{55} Compared with the cognitive tasks used previously, gripping the stick is a non-goal-directed, and nonspatially related motor action, which puts less demand on the concentration, memory, attention, and judgments affected by brain injuries.\textsuperscript{56} Therefore, holding an object in the hand could be assistive rather than distracting in regard to improving postural control, as suggested by our findings.

Finally, the fact that the current results are not consistent with previous studies in healthy individuals must be addressed. In prior studies, a tendency to decrease postural sway has been found in healthy participants holding a cane parallel to the ground during quiet stance,\textsuperscript{57} and in those gripping a load cell while standing on the floor,\textsuperscript{21} or on a rocker board.\textsuperscript{20} The discrepancy between our results and the prior results may be accounted for by ceiling effects. In healthy individuals, postural oscillations during quiet stance are minimal and have little room to decrease without negatively impacting body stability. To test this hypothesis in this study, we correlated the stability gain with the baseline level of postural oscillations. A moderate correlation was found ($r = 0.6$), wherein the stability gain tended to be larger for participants with more baseline sway. This result partially confirms the idea that the amount of improvement in postural stability depends on the amount left to be improved, although the influence of other factors cannot be excluded.\textsuperscript{58}

### Study Limitations

The TBI group was represented by a small and relatively heterogeneous group of individuals, with unique postinjury sensorimotor and cognitive deficits associated with traumatic head injuries. This prevents extrapolation of our findings to individuals with more severe postinjury deficits or those with other neurological and/or types of acquired brain impairments. The study did not investigate whether the suprapostural task of gripping a stick is effective for postural stabilization during regular activities of daily living. No detailed analysis of the latency and direction of postural responses to the visual stimulation was done, as the stimulation was used as a perturbation technique, not an approach to the investigation of the role of vision in postural control. We acknowledge that all these limitations may affect our findings.

### CONCLUSION

The results of this study suggests that holding a mobile object (short wooden stick) in the dominant hand reduces the displacement and velocity of postural sway and velocity in persons with TBI in the presence of a perturbation arising from the visual stimulation of a moving environment. Further research is needed to determine whether this technique will translate to improving functional activities of daily living, such as walking in crowded areas. Studies to identify the mechanisms underlying these findings would also be of value.

### REFERENCES
