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Original article

Effects of saccadic eye movements on postural control stabilization

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Abstract—Several structures of the central nervous system share involvement in both ocular and postural control, but the visual mechanisms in postural control are still unclear. There are discrepant evidences on whether saccades would improve or deteriorate stabilization of posture. The purpose of this study was to determine the influence of saccadic eye movements on postural control while standing in different basis of support. Twelve young adults stood upright in wide and narrow stances while performing fixation and saccades of low and high frequencies. Body sway was attenuated during saccades. Trunk anterior-posterior sway and trunk total displacement decreased during saccades compared to fixation; higher sway mean frequency in anterior-posterior direction during saccades was observed. Body sway was reduced in wide compared to narrow stance during high frequency saccades. These results indicate that eye movement improves postural stabilization and this effect is stronger in combination of wide stance-high frequency gaze condition.

Keywords: saccades, eye movements, posture

Resumo—“Efeitos dos movimentos sacádicos oculares na estabilização do controle postural.” Várias estruturas do sistema nervoso central compartilham envolvimento nos controles ocular e postural, mas os mecanismos visuais no controle postural ainda não estão claros. Existem evidências discrepantes sobre a possibilidade de movimentos sacádicos melhorarem ou deteriorarem a estabilização postural. O objetivo desse estudo foi determinar a influência de movimentos sacádicos dos olhos sobre o controle postural em diferentes bases de apoio. Doze adultos jovens ficaram em pé, mantendo a postura sobre base ampla e restrita enquanto realizavam fixações e movimentos sacádicos de baixa e alta frequência. Oscilação corporal foi atenuada durante movimentos sacádicos. A oscilação do tronco na direção ântero-posterior e o deslocamento total do tronco diminuíram durante movimentos sacádicos comparados à fixação; maior frequência média de oscilação na direção ântero-posterior durante movimentos sacádicos também foi observada. Oscilação corporal foi reduzida em postura com base ampla comparada à restrita durante movimentos sacádicos de alta frequência. Estes resultados indicam que o movimento do olho melhora a estabilização postural e este efeito é mais forte na condição que combina base ampla e alta frequência do olhar.

Palavras-chaves: movimentos sacádicos; movimentos dos olhos, postura

Resumen—“Efectos de los movimientos sacádicos oculares en la estabilización de control postural.” Varias estructuras del sistema nervioso central comparten de participación en los controles ocular y de postura. Existen pruebas dispares sobre lo movimiento sacádico mejorar o deteriorar la estabilización postural. El objetivo de este estudio fue determinar la influencia de los movimientos oculares sacádicos sobre el control postural en diferentes bases de apoyo. Doce jóvenes quedaram de pie manteniendo la postura de base amplia y restringido mientras hacian fijaciones y movimientos sacádicos de baja y alta frecuencia. Lal oscilación del cuerpo fue atenuada durante los movimientos sacádicos. La oscilación del tronco en dirección antero-posterior y el desplazamiento total del tronco han disminuido durante los movimientos sacádicos comparados con fijación; también se ha observado mayor frecuencia media de oscilación en la dirección anteroposterior durante los movimientos sacádicos. La oscilación del cuerpo se redujo por la postura de base amplia en comparación con la restringida durante los movimientos sacádicos de alta frecuencia. Estos resultados indican que lo movimiento de ojo mejora la estabilización postural y este efecto es más fuerte para la condición de base amplia y alta frecuencia de la mirada.

Palabras claves: movimientos sacádicos, movimientos oculares, postura

Introduction

Integrating posture and search for visual information via eye movements provides crucial support for human activity over its environment. The detection of changes resulting from body movements is necessary for controlling body equilibrium. Due to spontaneous body oscillations, the image of the environment moves on the retina; this retinal slip (directly related to these oscillations) is used by the central nervous system as feedback for compensatory sway (Guerraz & Bronstein, 2008). However, participants who had to fixate a small light in a dark room, as compared to a completely dark room, largely reduced their spontaneous lateral body oscillations (Paulus, Straube, & Brandt, 1984); situations where the eyes track the light as the head is moving laterally, providing minimum or no retinal shift, suggest that head displacement can be sensed through the amplitude of eye movement, an extraretinal motion perception, not retinal slip (Guerraz & Bronstein, 2008). These findings had led to the notion that two different mechanisms subserve visual stabilization of posture: afferent and efferent motion perception. The afferent mechanism is based on characteristics of visual flow (retinal slip); the efferent one is based on either the copy of motor command (efference copy) or the extraocular muscle afferents (re-afferences) consecutive to eye movements (Guerraz & Bronstein, 2008).

Investigations of body sway during saccades have provided discrepant evidences. Particularly, it is not clearly established that saccadic eye movements would increase or decrease body oscillation. White, Post, and Leibowitz (1980) showed that the retinal slip resulting from voluntary saccades was not accompanied by postural destabilization; however, when a similar motion was produced in a stationary eye by moving the visual surroundings, posture was remarkably affected indicating that body sway depends on whether movement of the retinal image is voluntarily or externally produced. Rougier and Garin (2007) reported that performing saccadic eye movements reduced the amplitude of body displacements. Rey, Lê, Bertin, and Kapoula (2008), studying horizontal and vertical saccades at near and far distances, also found that saccadic movements reduced body sway as compared to fixation conditions. Similarly, Stoffregen, Bardy, Bonnet, and Pagulayan (2006) measured body sway during saccades performed with eyes opened and closed; when eyes were opened, postural sway was reduced during saccades, but eye movements made when eyes were closed did not yield such reduction on body sway. In addition, contribution of saccades to reduce postural sway did not depend on the frequency of horizontal saccades (0.5, 0.8, and 1.1 Hz) (Stoffregen, Bardy, Bonnet, Hove, & Pagulayan, 2007).

Differently, other studies have found that eye movements deteriorate postural stability. Hunter and Hoffman (2001) investigated the effects of varying visual demands paired with a concurrent cognitive task on postural stability and observed significantly greater sway variability in the eye movement condition compared to the no eye movement condition. Glasauer, Schneider, Jahn, Strupp, and Brandt (2005) demonstrated that movement of eyes during pursuit (with or without simultaneous head pursuit) consistently increased body sway in the contexts of complete darkness, space fixed target, and moving target. The authors argued that, besides typical influence of movement of the visual scene on balance control, eye movement signals have a direct influence on postural control, concluding that “the eyes move the body” (p. 1292). Patients with vestibular neuritis were studied as they wore a mask to allow fixation of a head-fixed target in order to suppress their spontaneous nystagmus and the observed suppression of nystagmus was associated with reduced postural sway while standing on foam rubber, which was interpreted as support for the notion that the visual stabilization of posture is not only dependent on afferent visual cues but also on ocular motor signals (Jahn et al., 2002; Strupp et al., 2003).

The studies revised above did not control systematically the effect of altering mechanical postural demands. Changes in the basis of support might reveal the limits the postural system accounts for particular perceptual manipulation. For instance, horizontal saccades could potentially induce lateral body sway if eye movements were to interfere with vestibular and retinal sources of information. In the present study, reducing the distance between heels was chosen to amplify lateral mechanical disturbances, in addition to perceptual ones possibly due to saccades. In the same vein, increasing saccadic frequency could reveal adaptations during more challenging postures. Additionally, combining eye movements and cognitive tasks (Hunter & Hoffman, 2001), having participants wearing a mask to suppress spontaneous nystagmus, investigating pathological populations (Glasauer et al., 2005; Jahn et al., 2002; Strupp et al., 2003), or using distinct eye behaviors, such as smooth pursuit (Glasauer et al., 2005) or bilateral blinking (Rougier & Garin, 2007) as previous studies have done, may not be directly comparable with the present study situation, which focused on intentional, planned saccades to known locations in healthy participants.

The purpose of the present study was to determine the influence of horizontal saccadic eye movements of low and high frequencies on body sway while standing in ‘wide’ (with feet parallel at comfortable angle and distance apart, hip wide) and ‘narrow’ stance (with feet parallel placed together at both the heels and toes). It was hypothesized that during saccades body sway would be attenuated. Also, higher frequency saccades would further attenuate body sway. Different bases of support were expected to clarify whether changes in postural demands interact with effects of saccadic eye movements on postural control performance.

Method

Participants

Twelve undergraduate students (three males, nine females) participated as volunteers in the present study; mean age 21.9 (SD = 3.6) years, body mass 69.4 (SD = 8.5) kg, and height 1.69 (SD = 0.06) m. Three participants wore corrective glasses or lens during the experiment; all other participants reported no history of visual impairment or corrected vision. All participants had no knowledge about the purposes of the experiment and reported no history of falls, dizziness, or postural instability. Participants signed written consent, and the local University Ethics Committee approved the procedures employed in this study.

Equipment and procedures

Prior to data collection, participants had reflective markers attached to their head (posterior part, right above the occipital bone) and trunk (between the scapulae) recorded by two video cameras (Sony DCR DVD 205 and 405-60 Hz). Participants stood barefoot at two bases of support, wide and narrow. In both bases, the participant’s feet were maintained parallel to each other but aligned with the shoulder (wide) or together (narrow).

While standing upright for 70 s (the first 10 seconds were not considered for analysis), in both wide and narrow stances, participants fixated or pursued a target that was displayed in a monitor positioned 100 cm away from them. The target was a filled circle in red with 2 cm of diameter in a white background (subtended visual angle of the target was approximately 1.15º) generated by the software Flash Mx (Macromedia) and presented in a LCD monitor (LG, Faltron L1952H, 50/60Hz, 0.8 A) of 37.5 by 30 cm. In the fixation condition, the target was displayed in the center of the monitor throughout the trial. In the pursuing condition, participants had to perform saccades directed to the target appearing in one side of the monitor, 9.75 cm away from the center, then disappearing and reappearing immediately in the opposite side. Saccadic movements were performed at two different frequencies: low and high, with target changing position at 0.5 and 1.1 Hz, respectively.

The total distance between the right side target and the left side target was 19.5 cm comprising a visual angle of 11º in the horizontal plane. This angle usually requires eye movements alone, that is, without moving the head. However, no instruction was given to participants about head movements. The experimenter checked participants’ appropriate eye movements through a small camera, positioned above the monitor. Three trials were performed in each condition, totalizing 18 trials per participant, with the order of conditions defined randomly.

Data analysis

The recorded video images of all trials were clipped and tridimensionally reconstructed and exportated based on the space coordinates of the tracked markers (Software APAS, Ariel Dynamics, version 1). Trunk sway mean amplitude and head sway mean amplitude in anterior-posterior (AP) and medial-lateral (ML) directions were calculated as the standard deviation of positional data throughout the trial; trunk total displacement and head total displacement were calculated as the total trajectory length of the respective marker during the trial; trunk mean frequency and head mean frequency were obtained via spectral analysis of the position time series, separately in each direction (software Matlab, Mathworks, version 5). Gaze (fixation, saccade 0.5 Hz, saccade 1.1 Hz) by stance (wide, narrow) repeated measures ANOVAs were carried out for each dependent variable (software SPSS, version 9). Tukey HSD tests, Greenhouse-Geisser degrees of freedom adjustments, and Bonferroni multiple comparisons probability adjustments were conducted as necessary (Maxwell & Delaney, 1990). The significance level adopted was $p \leq 0.05$ for all analyses.

Results

In the AP direction, amplitude of trunk sway was significantly affected by gaze, $F_{1.4, 15.8} = 10.011$, $p = 0.003$, as well as by the interaction gaze by stance, $F_{1.9, 21.2} = 3.665$, $p = 0.044$. Post hoc tests revealed that trunk sway was greater during fixation (0.75 cm) than during 0.5 Hz (0.56 cm) and 1.1 Hz (0.47 cm) saccades, *p*s = 0.016 and 0.017, respectively. Stance affected trunk sway amplitude only during saccades at 1.1 Hz ($p = 0.011$): trunk sway was significantly smaller in wide (0.42 cm) than in narrow stance (0.52 cm) (Figure 1, top left). Similarly, amplitude of head sway was significantly affected by gaze, $F_{1.4, 15.9} = 9.75$, $p = 0.003$. Post hoc tests revealed that head sway amplitude was greater during fixation (0.89 cm) than during 0.5 Hz (0.66 cm) and 1.1 Hz (0.59 cm) saccades, *p*s = 0.017 and 0.019, respectively. Also, head sway during wide stance (0.68 cm) was significantly smaller than during narrow stance (0.75 cm), $F_{1, 11} = 5.83$, $p = 0.034$. For the ML direction, trunk sway mean amplitude was significantly affected by gaze, $F_{1.6, 17.3} = 4.01$, $p = 0.046$, and by stance, $F_{1, 11} = 96.76$, $p < 0.001$. Post hoc tests showed no

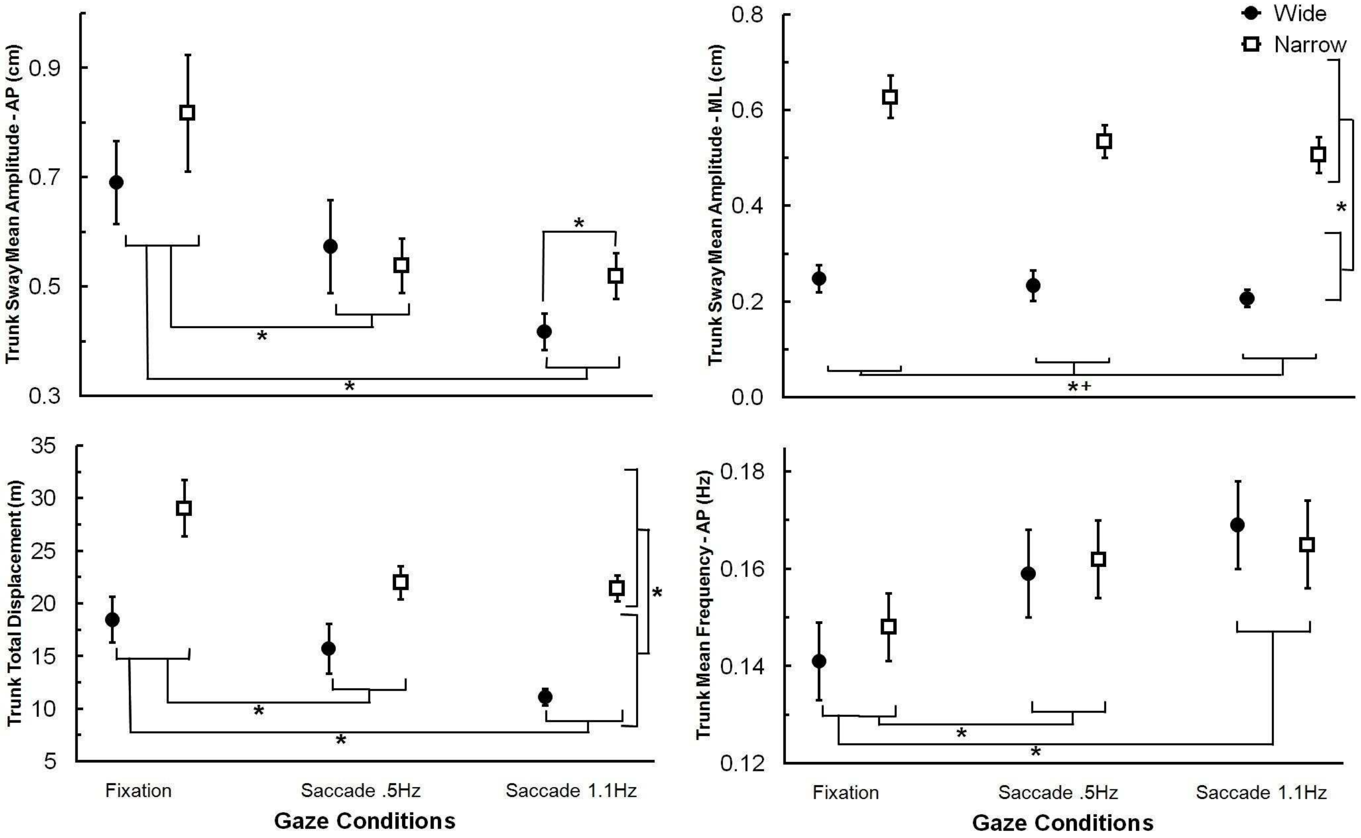

Figure 1. Mean and standard error of anterior-posterior (top left) and medial-lateral (top right) trunk sway mean amplitude, trunk total displacement (bottom left), and trunk mean frequency (bottom right) for the three gaze conditions (fixation, saccade 0.5 Hz, and saccade 1.1 Hz) and for the two stances (wide and narrow) * $p \leq 0.05$; + Post-hoc pairwise comparisons between gaze condtions were not significant.

significant differences in any pairwise comparison between gaze conditions. Trunk sway amplitude in wide stance (0.23 cm) was significantly smaller than in the narrow stance (0.56 cm) (Figure 1, top right). Similarly, head sway amplitude in the wide stance (0.29 cm) was significantly smaller than in the narrow stance (0.62 cm), $F_{1, 11} = 86.33$, $p < 0.001$.

Trunk total displacement was significantly affected by gaze, $F_{1.2, 12.7} = 12.23$, $p = 0.003$, and by stance, $F_{1, 11} = 96.74$, $p < 0.001$. Post hoc tests revealed that trunk total displacement was greater during fixation (23.75 m) than during 0.5 (18.82 m) and 1.1 Hz (16.26 m) saccades, $p < 0.001$ and $p = 0.011$, respectively (Figure 1, bottom left). Similarly, head total displacement was significantly affected by gaze, $F_{1.1, 12.3} = 11.87$, $p = 0.004$, and by stance, $F_{1, 11} = 84.38$, $p < 0.001$. Post hoc tests revealed that head total displacement was greater during fixation (27.63 m) than during 0.5 Hz (22.34 m) and 1.1 Hz (20.52 m) saccades, $p < 0.001$ and $p = 0.014$, respectively. In the AP direction, trunk mean frequency was significantly affected by gaze, $F_{1.6, 17.4} = 8.13$, $p = 0.005$. Post hoc tests revealed that trunk mean frequency was lower in the fixation (0.139 Hz) than in the 0.5 Hz (0.156 Hz) and 1.1 Hz (0.162 Hz) saccades, *p*s = 0.025 and 0.027, respectively (Figure 1, bottom right). Similarly, head mean frequency was significantly affected by gaze, $F_{1.5, 16.6} = 5.740$, $p = 0.018$, as well as by the interaction gaze by stance, $F_{1.9, 20.7} = 3.93$, $p = 0.038$. Main effect and interaction post hoc tests showed no significant differences in any pairwise comparison between gaze or stance conditions. In the ML direction, trunk mean frequency in the wide stance (0.25 Hz) was significantly higher than in the narrow stance (0.16 Hz), $F_{1, 11} = 53.29$, $p < 0.001$. Similarly, head mean frequency during wide stance (0.24 Hz) was significantly higher than during narrow stance (0.16 Hz), $F_{1, 11} = 39.83$, $p < 0.001$.

Discussion

The aim of this study was to analyze the effect of horizontal saccades of low and high frequencies on body sway measured during wide and narrow stances. The hypothesis was that saccades would attenuate body sway, with a stronger effect in the higher frequency condition. Overall, the results support both aspects of this hypothesis. First, the observed reduction in amplitude and total displacement and increase in mean frequency corroborate the notion of body sway attenuation during saccades. Second, the combination of wide stance and higher frequency saccades further attenuated body sway as expected.

The reduction of body sway during saccadic eye movements confirms previous findings (Rey et al., 2008; Rougier & Garin, 2007; Stoffregen et al., 2006; White et al., 1980) suggesting that gaze activity itself does not generate a more pronounced body oscillation. Saccadic suppression was not capable of disrupting postural control; in comparison to fixation, saccade conditions seemed to require greater postural stability to allow spatially more accurate gaze shifts indicating a functional integration of postural and gaze control (Stoffregen et al., 2006). Other studies that found that eye movements deteriorate postural stability employed different methods and included individuals with eye disorders, which may account for their opposite conclusions. Present results can be explained based on the afferent and efferent mechanisms of visual stabilization of posture (Guerraz & Bronstein, 2008). Via afferent mechanism, individuals try to minimize the changes of the projected image on the retina in order to keep the relationship between visual information and body posture stable during fixation. It is relevant to acknowledge that short-term fixations also occur between saccades in both 0.5 and 1.1Hz conditions. Although these fixations were not recorded, their duration supposedly varied according to the saccadic frequency condition. The efferent mechanism (particularly, efference copy) actuates by attenuating body sway in an attempt to connect pre-saccadic and post-saccadic views of the scene (Kowler, 2011), which favors the spatial accuracy of the saccade with respect to the target location. This mechanism could explain the main effect of gaze condition in the present study, but not the gaze by stance interaction. The further reduction of body sway during wide stance as participants performed higher frequency saccades could be understood if the efferent mechanism's efficacy in reducing body sway were modulated by the combination of short-term fixation duration (time available for anticipatory planning of the next saccade) and stance difficulty. When the time available for saccadic planning is sufficient, stance difficulty does not change body sway; however, when this time is not sufficient, efferent mechanism's efficacy in reducing body sway increases only in the easy (wide) stance. This reasoning seems in line with the notion of adaptive resource sharing (Mitra, 2004), although this interpretation has limitations regarding inferences on durations of saccades, short-term fixations or even saccadic velocity because line-of-gaze kinematics was not measured.

Stoffregen et al. (2007) hypothesized that the amplitude of postural sway would scale negatively to the frequency of eye movements but they did not confirm such effect. No differences in body sway were observed among the frequencies of 0.5, 0.8 and 1.1 Hz. Additionally, they conducted a dominant frequency (principal peak in the power frequency spectrum) analysis and found that it was not influenced by the presence or frequency of eye movements. Differently, the present data showed significant effects related to the frequency of both body sway and saccades: (i) the trunk mean frequency was affected by condition, and (ii) the frequency of saccades could affect posture differently depending on the stance difficulty. This second item corroborates an adaptive resource-sharing interpretation (Mitra, 2003; 2004; Mitra & Fraizer, 2004). In such view, control of body posture and control of suprapostural tasks access the same capacity-limited resources, which need to be shared between tasks. The sharing process is governed by factors such as precision required, utility, and demands of information acquisition in support of each task component (Mitra, 2004). Nevertheless, the reduction of body sway during the saccade conditions confirms an improvement of postural control (Stoffregen et al., 2006; Stoffregen, Smart, Bardy & Pagulayan, 1999) due to eye-controlled movement.

Better understanding how eye movements changed the control of body sway in a relatively simple, controlled and predictable situation as the one employed in this study has provided some elements to extrapolate to more complex, dynamical and challenging environments. In summary, this study showed that body sway was attenuated during saccades as hypothesized previously. During the saccade conditions, afferent and efferent mechanisms (Guerraz & Bronstein, 2008) were capable of reducing body oscillation to levels lower than fixation. Higher saccadic frequency further attenuated body sway only during wide stance, revealing how gaze and stance effects interacted. The effect of reducing time for anticipatory planning of the next saccade (efference copy) during 1.1 Hz condition was dependent of the stance difficulty. Facilitating gaze performance by additional attenuation of body sway was possible only during the easy (wide) stance. In addition to measure eye movements, future studies should address the effects of distinct basis of support on the control of gaze and posture in more natural situations, such as watching a table tennis match or playing a videogame.

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