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Trunk and head displacements stabilized to perform both horizontal and vertical saccadic eye movements

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Abstract

Vision is crucial for humans to interact with their surrounding environment, and postural sway is reduced to allow short saccadic eye movements. However, the extent of subtle changes in postural control for horizontal and vertical saccadic eye movements remains unclear. The goal of this study was to investigate the effects of vertical and horizontal saccadic eye movements on head and trunk control in young adults. Fifteen healthy adults (23.4±4.7 years) stood upright in three conditions for 60 s: fixation, horizontal, and vertical guided eye movements. In fixation, participants had to fixate on a stationary target. In both the horizontal and vertical eye movements, the target was presented with a frequency of 0.5 Hz and a visual angle of 11 °**.** Eye displacement was monitored using a SMI eye tracker (ETG2.0) and trunk and head sway were monitored using infrared markers (Optotrak 3020, NDI). The mean sway amplitude was lower in both directions for eye movements and lowest in the vertical direction compared to the fixation condition. The sway area was also lower in vertical movement than in the fixation condition. We also found that the reduction was greater at head level than at trunk level. The median frequency sway in the anterior-posterior direction was higher in both eye movements than in fixation. Based upon these results, we suggest that to perform short saccadic eye movements, postural sway is more strongly controlled at the head level than at the trunk and in vertical saccadic eye movements than in horizontal movements.

Keywords: Postural control; Vision; Saccades; Coordination.

Introduction

Vision is continuously used to explore and obtain information to guide body movement in the environment. Visual information also plays an important role in postural control and the maintenance of balance (Lee and Lishman, 1975). In the 20th century, body sway magnitude was shown to be significantly reduced in the fixation of a stationary target with open eyes (fixation tasks) compared to when the eyes were closed (Paulus et al. 1984). More recently, in the 21st century, researchers have consistently shown that body sway is reduced to perform visually guided saccadic eye movements in the upright stance, in comparison to fixation in young adults (Stoffregen et al. 2006; Rey et al. 2008; Bonnet and Baudry 2016; Thomas et al. 2016), elderly people (Aguiar et al. 2015), and children (Ajrezo et al. 2013; Bucci et al. 2014).

It is now well accepted that a reduction in postural sway in guided eye movements leads to increased visual stability to perform more spatially accurate saccades (Rodrigues et al. 2013; Bonnet and Baudry 2016). When guided eye movements are performed in the upright standing position, postural sway is reduced to allow accurate gaze shifts, which is an indication of a functional relationship between posture and gaze control (Stoffregen et al. 2006). This functional relationship has been suggested to be attained by afferent (minimizing the changes in the projected image on the retina) and efferent (attenuating postural sway in an attempt to connect pre- and post-saccadic views of the scene) mechanisms (Guerraz and Bronstein 2008). Another possibility is that improvement of postural control to perform eye movements is due to increased proprioceptive signals from extra-ocular muscles and/or a shift in attention (Rey et al. 2008).

Many researchers have examined postural control in horizontal eye movement tasks *versus* control fixation tasks (Stoffregen et al. 2006; Stoffregen et al. 2007; Rey et al. 2008; Giveans et al. 2011; Irving and Lillakas 2019; Polastri et al. 2019). Much less is known about eye movements in the vertical direction, which may be due to the greater importance attributed to horizontal eye movements because we use them more often in ongoing activities (Foulsham et al. 2011), for example, when we read text. In an earlier publication, authors suggested that the mechanisms for horizontal and vertical saccades should be similar (Smit et al. 1987). However, we presume that the results of postural control are different in horizontal and vertical guided eye movements. Indeed, the two orientations of motion are both neurophysiological and anatomically distinct (Leigh and Zee 2006). Moreover, performing vertical eye movements might increase head rotation more than during horizontal eye movements, as shown in previous studies (Fukushima et al. 2007; Polastri et al. 2019).

The lack of or little attention to the use of vertical eye movements for postural control is somewhat surprising since, in our environment, the vertical motion of objects is common and in line with gravity. For instance, gravity-congruent visual motion is associated with reduced sway compared to gravity-incongruent and horizontal stimulus motion in adults standing upright (Balestrucci et al. 2017). Based upon these findings, it was suggested that dynamic visual cues coherent with gravitational field direction are functionally used for postural control and that the neural processing of the visual cues associated with other sensory cues (such as vestibular cues) provides a predictive and matching internal model that improves postural control (Balestrucci et al. 2017). In contrast, postural stability did not improve when young adults were asked to follow moving dots in the horizontal and vertical directions when standing on an unstable platform (Vagaja and Bizovska 2019).

In brief, new information needs to be uncovered regarding the use of vertical eye movements in postural control, especially in comparison with horizontal eye movements. Therefore, the aim of this study was to investigate the effects of guided eye movements in vertical and horizontal directions on head and trunk control in young adults. We hypothesized that the attenuation effect on the magnitude of sway would occur for both horizontal and vertical eye movement conditions but would be larger in horizontal eye movement conditions, since horizontal eye movements are more often employed in the daily activities (Foulsham et al. 2011). Furthermore, we expected, assuming an inverted pendulum model in maintaining an upright stance (Winter et al. 1998), that head sway would be larger than trunk sway and that postural sway would be reduced as a whole and not only at the head level.

Methods

Participants

Fifteen healthy undergraduate students (23.4 ± 4.7 years, 6 males and 9 females) participated in this study. All participants had normal vision or corrected-to-normal vision with glasses or contact lenses. Participants had no knowledge of the purpose of the experiment and reported no history of falls, dizziness, or postural instability. Prior to the experimental procedures, the participants signed a written consent form with all procedures approved by the Institutional Ethics Committee.

Procedures

Participants wore an eye movement tracking system (Eye Tracking Glasses – ETG2.0 SMI) to capture eye displacement (iViewETG SMI – version 27.1). Four IRED markers (Optotrak 3020 – NDI) were attached (Rodrigues et al. 2013; Rodrigues et al. 2015) to the participant: one on the participant’s back (at approximately the 8th thoracic vertebra) and three in a triangle shape cluster (Smart Marker Rigid Body - NDI) that was strapped to the participant’s head. Tridimensional coordinates from the trunk and from one marker on the head (the one on the top of the triangle shape cluster) were used to analyze trunk and head sway in the anterior-posterior (AP) and medial-lateral (ML) directions.

Participants stood inside a small room (0.90 x 1.10 x 1.85 m in width, depth, and height, respectively) with black walls. The eye-movement tracking system was then calibrated when participants fixated specific target and eye positioning was indicated and recorded. During recordings, participants were instructed to stand as still as possible, with their feet parallel and spaced apart at pelvis width, and their arms hanging at their sides. Participants performed three experimental conditions: (1) fixation, (2) horizontal, and (3) vertical guided eye movements. In the three conditions, participants were 1 m away from the monitor (LG, model Flatron L1753T8) positioned at their eye level. In the fixation condition, participants fixated on a target (a 1.5-cm diameter black circle, with a visual angle of approximately 1.15 °) displayed in the center of the monitor and surrounded by a white background. In the horizontal and vertical guided eye movement conditions, participants gazed at a target that appeared and disappeared on the left and right, as well as the top and bottom sides of the monitor (9.75 cm from the monitor center), at a visual angle of 11 ° in the horizontal and vertical directions, at a frequency of 0.5 Hz, controlled by specific software (Flash Mx, version 6.0) (Rodrigues et al. 2013; Rodrigues et al. 2015). In both cases, only eye movements (and no head displacement) were necessary to perform the task because of the short distance between the participants and the target, and the small visual angle of the appearance of the stimulus (Rodrigues et al. 2013). It is well known that only eye movements are useful to perform eye movements lower than 15° .

Each condition was repeated three times, with each participant performing a total of nine trials. The trials were randomized in blocks of three (one block for each condition). Eye displacement was also monitored online, throughout each trial inspecting eye position made available by the eye tracking system, to ensure compliance with the instructions on how to perform each experimental condition. Based on this online inspection, one of the experimental investigators was able to visually confirm that all participants performed the tasks as required.

Data analysis

For postural sway, tridimensional coordinates for the trunk and head markers were filtered using a second-order digital Butterworth filter with a cutoff frequency of 5 Hz. Using the displacement of these two markers in the ML and AP directions, the following sway variables were calculated: sway area, mean sway amplitude, and median sway frequency. The sway area corresponded to the 95% confidence ellipse area of the head and trunk dispersion when the displacements of both directions were considered together. The mean sway amplitude, which was used to estimate trunk and head stability in each direction, was obtained by removing a linear trend from each data point of the individual ML and AP time series and then calculating the standard deviation. High or low values of the mean sway amplitude indicated less or more trunk and head stability, respectively. The median sway frequency was obtained by performing a fast Fourier transformation of the ML and AP time-series data and obtaining the corresponding frequency to half of the total power spectrum area for each trial. The mean sway frequency was used to further examine postural control. In this regard, increasing or decreasing values indicated better or worse postural control, respectively, as a strategy to reduce or increase postural sway.

Finally, Pearson's linear correlation coefficients were obtained between trunk and head displacements, for both AP and ML directions. Coefficient values close to 1 indicate that trunk and head were dependent to each other, meaning that both segments sway together.

Statistical analysis

After identifying the normality and homogeneity of variance assumptions, an analysis of variance (ANOVA) and two multivariate analyses of variance (MANOVA) were employed with visual condition (fixation, and horizontal and vertical eye guided movements) and body segment (trunk and head) as factors; both were treated as repeated measures. The dependent variable for the ANOVA was the sway area, and the dependent variables for the two MANOVAs were the mean sway amplitude and the median frequency sway for both ML and AP directions. Finally, another MANOVA was employed with visual condition as factor, also treated as repeated measure, and dependent variables were the correlation coefficients between trunk and head displacements for both AP and ML directions. When necessary, univariate analyses and post hoc tests with Bonferroni adjustments were performed. All analyses were performed using SPSS software, and ANOVA/MANOVAs were performed with the significance level set at 0.05.

Results

The participants were able to perform fixation and guided eye movements to the specific target well. Fig 1 depicts a representative time series of gaze position for the horizontal and vertical directions in all three conditions, illustrating task accomplishment by the participant.

Please insert Figure 1 here

Postural control

Fig 2 depicts the sway area for the trunk and head for all three conditions. ANOVA showed a significant difference for condition ($F_{2,28} = 7.54$, $p = 0.002$, $\eta p^2 = 0.350$) and body segment ($F_{1,14} = 21.80$, $p < 0.001$, $\eta p^2 = 0.609$), but there was no significant interaction between the two. Post hoc tests showed that the sway area, for both the trunk and head, was significantly lower in vertical guided eye movement than in the fixation condition. Moreover, the sway area was significantly larger for the head than for the trunk.

Please insert Figure 2 here

Fig 3 depicts the median sway amplitude for both the trunk and head in all three visual conditions. MANOVA revealed a significant difference for condition (Wilks' Lambda = 0.496, $F_{4,54} = 5.67$, $p = 0.001$, $\eta p^2 = 0.296$) and body segment (Wilks' Lambda = 0.169, $F_{2,13} = 31.92$, $p < 0.001$; $\eta p^2 = 0.831$), but there was no significant interaction. Univariate analyses showed a significant condition effect for both the AP ($F_{2,28} = 9.36$, $p = 0.001$, $\eta p^2 = 0.401$) and ML ($F_{2,28} = 3.48$, $p = 0.04$, $\eta p^2 = 0.199$) directions. In the AP direction, post hoc tests indicated that the mean sway amplitude was significantly larger in the fixation condition than in the horizontal and vertical guided eye movements. No difference was observed between the horizontal and vertical guided eye movement conditions ($p > 0.05$). For the ML direction, post hoc tests indicated that the mean sway amplitude was significantly larger in the horizontal than in the vertical guided eye movement. Univariate analyses showed body segment effects for both AP ($F_{1,14} = 60.62$, $p < 0.001$, $\eta p^2 = 0.812$) and ML ($F_{1,14} = 17.72$, $p = 0.001$, $\eta p^2 = 0.559$). The mean sway amplitude was significantly larger for the head than the trunk segment for both the AP and ML sway directions.

Please insert Figure 3 here

Fig 4 depicts the median sway frequency for both the trunk and head in all three visual conditions. MANOVA revealed a significant difference for condition (Wilks' Lambda = 0.413, $F_{4,11} = 3.90$, $p = 0{,}033$, $\eta p^2 = 0{,}587$) and body segment (Wilks' Lambda = 0.600, $F_{2,13} = 4.34$, $p = 0.036$, $\eta p^2 = 0.400$) but no significant condition or body segment interaction. Univariate analyses showed a significant condition effect only in the AP direction ($F_{2,28} = 7.04$, $p = 0.003$, $\eta p^2 = 0.335$). Post hoc tests indicated that the median sway frequency was significantly lower in the fixation condition than in the horizontal and vertical guided eye movement conditions. Univariate analyses showed no significant body segment effects in either the AP or ML directions ($p > 0.05$).

Please insert Figure 4 here

Table 1 depicts the correlation coefficients between the trunk and the head in all three visual conditions for both AP and ML directions. MANOVA did not reveal a significant difference for condition (Wilks' Lambda = 0.662, $F_{4,11} = 1.40$, $p > 0.05$, $\eta p^2 = 0.338$). Coefficient values (≥ 0.90) indicated that the trunk and the head sway were related to each other and the lack of difference among conditions indicated that both trunk and head segments synchronization was similar in all the eye movement conditions.

Please insert Table 1 here

Discussion

The purpose of this study was to examine the control of trunk and head movements to perform saccadic eye movements in horizontal and vertical directions in young adults. Our results showed that postural sway was reduced in both vertical and horizontal eye movements, but more so in the vertical movements. The median sway frequency increased in the AP axis in both eye movement conditions. Consistent with our second hypothesis, head sway was greater than trunk sway.

Sway magnitude reduction to perform guided eye movements has been observed in many studies involving horizontal eye movements in young adults (Stoffregen et al. 2006; Rey et al. 2008; Rodrigues et al. 2013; Thomas et al. 2016), elderly people (Aguiar et al. 2015), and children (Ajrezo et al. 2013; Bucci et al. 2014). Several researchers have also shown a reduction in sway magnitude when vertical eye movements are performed (Rodrigues et al. 2015; Polastri et al. 2019). Based upon our results, we consistently showed a significant reduction in the mean sway amplitude in the AP direction (Fig 3) in both horizontal and vertical eye movements and, therefore, we validated our hypothesis that stated reduction of sway magnitude for both horizontal and vertical eye movements.

Originally, we expected that the values for body sway stabilization would be larger to preferentially perform horizontal saccadic eye movements. Our results, however, led us to invalidate our hypothesis because they showed that postural stabilization was more pronounced in performing vertical eye movements (Fig 2 and 3). In fact, our results showed that the reduction in sway area was only observed in the vertical eye movement condition, not in the horizontal eye movement condition, compared to the fixation condition (Fig 2). Moreover, in the vertical eye movement condition vs. horizontal eye movements, we observed a greater reduction in mean sway amplitude in the ML direction (Fig 3). Based upon these results, body sway stabilization may be more useful in performing vertical guided eye movements than horizontal ones. Hence, we do not corroborate previous results obtained when young adults stood on an unstable surface, or when there was no difference in stability between vertical and horizontal moving visual stimuli (Vagaja and Bizovska 2019). On the other hand, visual motions congruent with the gravity line provided further reduction of postural sway magnitude in adults standing upright and suggested that visual dynamic gravitational cues seem to be involved in postural control functioning (Balestrucci et al. 2017).

Postural control was improved to successfully perform vertical eye movements despite the predominance of horizontal eye movements in daily life activities (Foulsham et al. 2011). One reason for this may be that postural control is more unstable, that is, postural sway may increase more easily in performing up-down rather than left-right saccadic eye movements. This is due to the fact that individuals sway more in the AP direction than in the ML direction and that there are many more degrees of liberty in the frontal plane than in the sagittal one (e.g. rotation of the knee only in the frontal plane, rotation at the hip and at the level of the vertebrae column larger forward/backward than on the side …). Furthermore, Fukushima et al. (2007) explained that when the head moves in an up-down motion (rotation in the pitch direction), the center of mass of the head is moved further away from its position than when the head turns in a left-right motion (rotation in the yaw direction). As the head is a heavy body segment, turning the head in the pitch direction automatically leads the body to sway more than turning the head in the yaw direction does. In fact, with similar amplitudes of head rotations vertically and horizontally, the center of mass of the head is further displaced in vertical as opposed to horizontal saccadic eye movements. As postural sway needs to be reduced to succeed in gaze shift tasks, postural sway should be more carefully controlled, that is, postural control requires further improvement to perform vertical eye movements. This postural control strategy would prevent any increase in postural sway caused by vertical saccadic eye movements. This explains why attention dedicated to postural control has already been found to be higher in vertical saccadic eye movements (Tzelepi et al. 2010).

Furthermore, the sway frequency results indicate possible reasons for sway amplitude reduction when the participants performed horizontal and vertical eye movements (Fig 4). In fact, we observed that sway frequency was increased in the AP direction in both eye movement conditions (Fig 4), indicating stronger postural control in the AP axis (Winter et al. 1998). Hence, this result is in line with a reduction in AP postural sway in the saccadic vertical and horizontal eye movement conditions. Overall, our results led us to advance knowledge of the use of visual information, regarding the horizontal and vertical saccades, in postural control.

Finally, postural sway was always larger for the head than for the trunk (Fig 2 and 3), despite both segments moving coherent and strongly related to each other (Table 1) in all eye movement conditions. These results thus validate our second hypothesis showing that even in performing saccadic eye movements of 11°, the body can mimic an inverted pendulum with the ankle most likely functioning as the pivot (Winter et al. 1998; Karlsson and Frykberg 2000). This conclusion is further strengthened by the fact that horizontal and vertical eye movements reduce the sway of the whole body, trunk and head in this study. This result is important because the head could have been stabilized in space by moving all body segments in various ways; for example, around the trunk using ankle and hip strategies (Creath et al. 2005). However, our Pearson correlation analyses showed that healthy young adults preferred swaying as an inverted pendulum in all vision conditions employed in this study. In other words, we observed that guided eye movement tasks involving small displays (up to 11 °) do not lead to any changes in how trunk and head are related to each other as an individual sways in the anterior-posterior and medial-lateral directions.

In summary, this study showed that postural sway in the upright stance was stabilized to successfully perform both horizontal and vertical guided eye movement tasks. Most importantly, postural sway was further stabilized for vertical eye movements compared to horizontal eye movements. The reduction of postural sway has practical implication for the performance of standing tasks, as previously indicated (Zemková and Hamar 2014), and the use of vertical eye movements in daily activities should be further examined in future studies with new visual environments.

Declarations

Funding: No funds, grants, or other support was received.

Conflict of interest: The authors have no conflicts of interest to declare that are relevant to the content of this article.

Availability of data and material: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability: Not applicable

Ethics approval: All procedures were approved by the Institutional Ethics Committee, Institute of Biosciences, São Paulo State University.

Consent to participate: Prior to the experimental procedures, the participants signed a written consent form

Consent to publish: Participants signed informed consent regarding publishing their data.

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Figure Legends

Fig. 1 Representative time series of gaze position for both horizontal (left panels) and vertical (right panels) directions in all three visual conditions: fixation (a, b), horizontal (c, d), and vertical (e, f) guided eye movements

Fig. 2 Mean and standard error for sway area for both the trunk and head in all three visual conditions (fixation, horizontal, and vertical guided eye movements). Note: * denotes a significant difference

Fig. 3 Mean and standard error for median sway amplitude in the anterior-posterior (a) and medial-lateral (b) directions for both trunk and head in all three visual conditions (fixation, horizontal, and vertical guided eye movements). Note: * denotes a significant difference

Fig. 4 Mean and standard error for median sway frequency in the anterior-posterior (a) and medial-lateral (b) directions for both the trunk and head in all three visual conditions (fixation, horizontal, and vertical guided movements). Note: * denotes a significant difference

Table 1 Mean and standard deviation correlation coefficients between the trunk and the head in all three conditions for both anterior-posterior and medial-lateral directions.

Conditions Directions	**Fixation**	**Horizontal**	**Vertical**
Anterior-posterior	0.95 (0.04)	0.93 (0.06)	0.94 (0.04)
Medial-lateral	0.90 (0.07)	0.91 (0.06)	0.92 (0.05)

Figure 1.

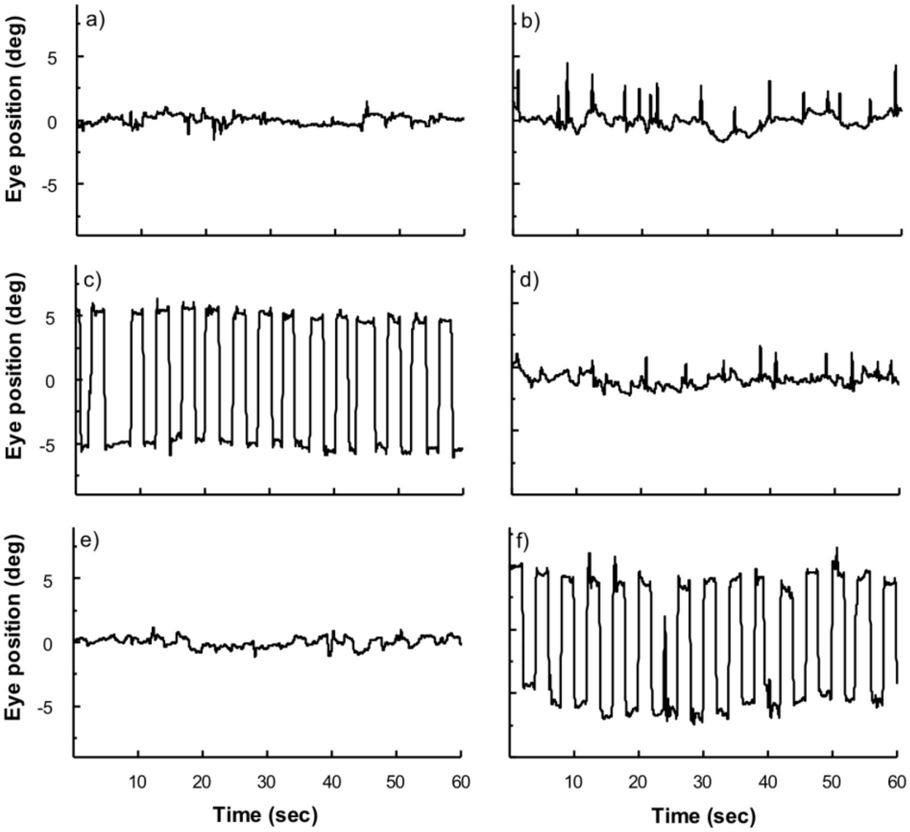


Figure 2.

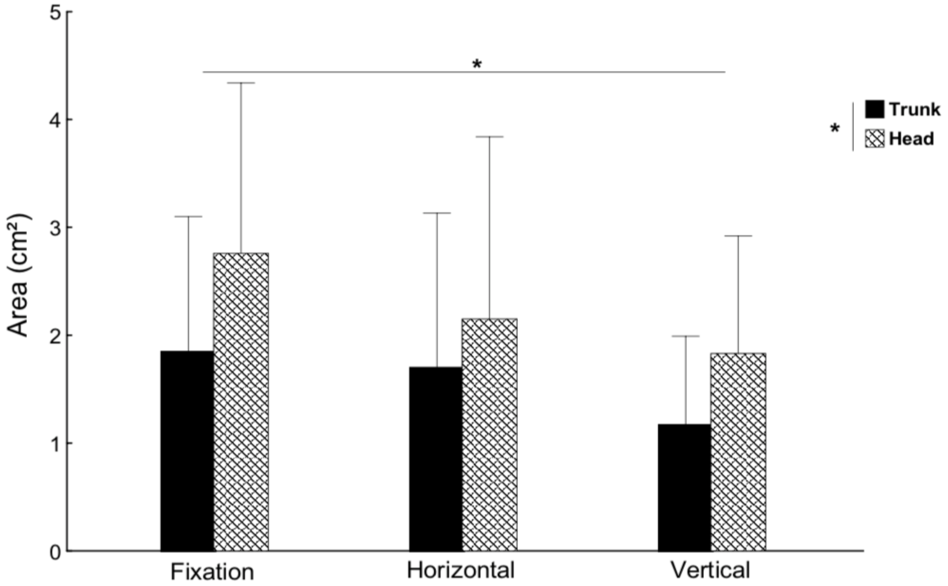


Figure 3.

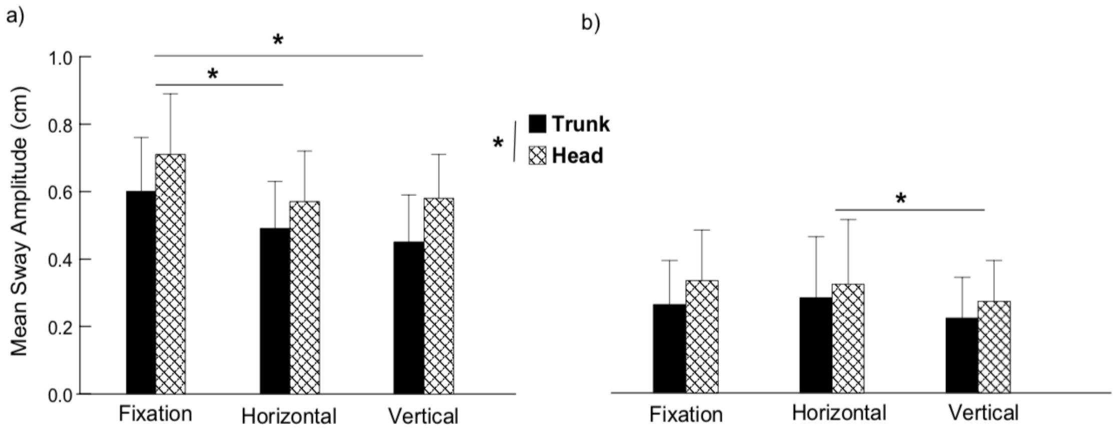
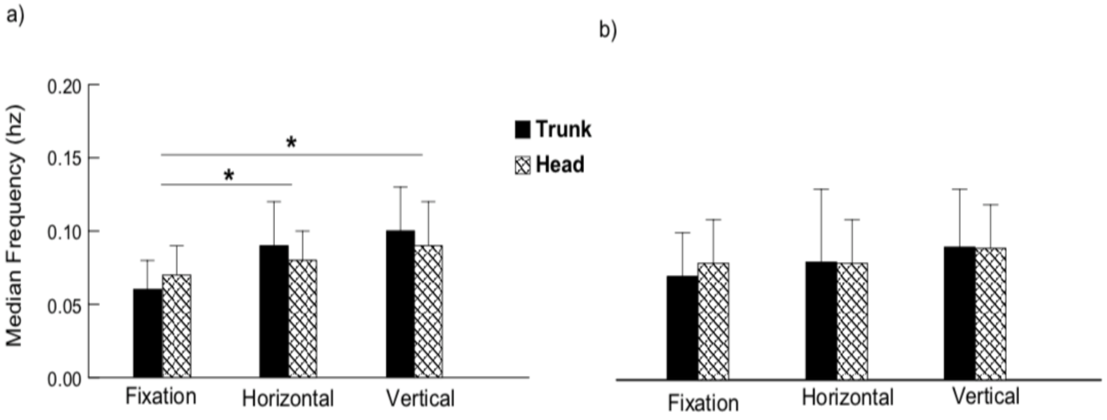

a)
b)
Mean Sway Amplitude (cm)
1.0
0.8
0.6
0.4
0.2
0.0
*
*
*
Trunk
Head
*
Fixation
Horizontal
Vertical
Fixation
Horizontal
Vertical

Figure 4.


a)
b)
Median Frequency (hz)
0.20
0.15
0.10
0.05
0.00
*
*
Trunk
Head
Fixation
Horizontal
Vertical
Fixation
Horizontal
Vertical