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Original Article

The role of eye movement in upright postural control

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Abstract

Vision contributes to upright postural control by providing afferent feedback to the cerebellum. Vision is generally classified into central and peripheral vision. In measurements of postural sway, in which participants are required to maintain a stable upright posture while fixating on a visual target, non-retinal eye positional information due to the fixation is used as well as the retinal information from both visual fields. However, little is known about the role of non-visual eye positional information in postural control. This study examined the role of non-visual eye position information in upright postural control by comparing participants' centre of pressure (COP) sway between two experimental conditions: (1) a space-fixed visual target condition (control), in which eye movement was not controlled, and (2) a head-fixed visual target condition (treatment), in which eye movement was inhibited. Using 12 university students, COP sway and electrooculograms (EOG) were measured under both conditions. In the space-fixed condition, participants maintain an upright posture while fixating on a visual target fixed on a screen 1 m in front of them. In the headfixed condition, participants maintained an upright posture while gazing at a target moving in sync with their head sway on the screen. The COP was evaluated by path length, area, root mean square, velocity and position. Eye movements were evaluated by the mean eye movement angle. The mean eye movement angle was significantly larger in the vertical direction then in the horizontal direction in both experimental conditions and was also found to be larger in the space-fixed condition than in the head-fixed condition. No significant different was found in any COP parameter between both conditions. It was suggested that non-visual eye position information from the external eye muscles to the sensory perception system contributes little to postural stabilisation under the measurement conditions used in this study.

Key-words: Young adults · Equilibrium test · Balance · Eye position information

Introduction

In order to maintain a bipedal upright standing stance without falling, we need to sustain and control the position and momentum of the centre of gravity of our entire body through a narrow base of support [1, 2]. For adequate postural control, humans normally keep revising a collapsing posture by integrating vestibular, visual and somatosensory information in the central nervous system from the whole body and by properly assessing the position and motion of the body in space [3, 4]. Many studies on upright standing postural control have used centre of pressure (COP) as an output measure.

The vestibular and proprioceptive systems detect information internal to the body, and the visual system detects information related to the external environment separate from our body [5, 6]. COP sway markedly increases while standing in a dark room or with eyes closed [3, 7, 8]. A decrease in visual functions largely influences postural control and interferes with daily-life activities [9]. Because the elderly have a higher dependence on the visual system for postural control than young adults [10, 11], their fall accidents increase due to impaired visual functions.

Jahn et al. [12] reported that "The effect of vision on stabilising posture has been widely examined in clinical settings [13–16]. These reports suggested that optic flow [17] caused by a wide range of external environment movements is reflected on the retina as a wide range of retinal slip, and retinal slip has an important role on the visual stabilisation of posture. For example, Gibson [17] and Lishman and Lee [18] reported that with a moving external environment (the visual image on the retina), participants lean to the direction of the movement of the visual image." As above, it is known that there is a close relationship between self-motion perception and retinal slip on a broad area of the peripheral visual fields, including the peripheral visual field.

In contrast, there are few studies reporting that central vision contributes to the stabilisation of posture. While maintaining an upright standing posture while fixating on a point of light fixed in a completely dark room, people may experience a unique sensation that the fixation point is moving but may not perceive their own self-motion. Under these conditions, the person is trying to maintain their postural stability by sensing body sway based on information from various sensory systems, including (1) the visual system, which detects visual information provided only in the central visual field, (2) the vestibular sensation system, which detects acceleration of the head, and (3) the somatosensory system, which detects plantar pressure.

Specifically, eye movements occur to pursue the visual target with the central fovea, which is a most sensitive point in the visual field, while maintaining an upright posture and fixating on the visual target fixed in a dark room. The eye movements may include smooth pursuit and the vestibuloocular reflex (VOR). While the ocular following response (OFR) is reflexively induced by widerange movement in the visual fields, the smooth pursuit is an advanced voluntary eye movement that traces a visual target moving slowly in the central visual field. The VOR is a reflexive eye movement used to stably maintain the direction of the eyes toward the visual target while the head is moving. This reflex is induced when the vestibular system detects a movement of the head that interrupts stable fixation, and the central nervous system gives a command to move the eyes so as to cancel the head motion.

Therefore, while fixating on a fixed visual target in a dark room, eye position information is sent by the ocular muscles to the sensory system simultaneously and in addition to the visual information, which acts as a trigger for the eye movements, namely the retinal slip within the central fovea. This non-visual eye position information is known to have an important role in the consistency of the visual world [19]. It was reported that participants could maintain their eye direction to the direction indicated previously with considerable accuracy, even in a completely dark room without any visual cues [19]. In this case, the cue available to the participants while fixating is the only information regarding eye position inside the eyepit, namely the non-visual eye position information. Therefore, it is suggested that the spatial orientation of the participants is maintained with considerable accuracy if participants cannot obtain visual information.

We revealed in our previous study that body sway velocity became lower when participants, who were maintaining an upright standing posture in a dark room, were presented with a visual target as compared to the condition in which they received no visual cue [20]. This suggests that fixation in a dark room has the possibility to contribute to postural stabilisation. It is possible that either the visual information, induced by fixating, or the non-visual information contributes to the postural stabilisation, even in the case of upright standing posture with fixation on a visual target, such as in the equilibrium test. However, the influence of the non-visual information, due to central vision, on postural control has not been well studied previously. In this study, it was hypothesised that in the task of maintaining an upright standing posture, which is required in daily life, COP sway, as an output of postural control, changes with the suppression of eye movement.

To examine the influence of non-retinal, non-visual eye position information on postural control while maintaining an upright standing posture and fixating on a visual target, we compared the participants' COP sway between two experimental conditions: (1) a control condition (space-fixed visual target condition), in which eye movement was not controlled, and (2) a treatment condition (head-fixed visual target condition), in which eye movement was inhibited.

Materials and Methods

Subjects

Twelve healthy males (age, 21.7±2.1 years, height, 172.2±4.4 cm, body weight, 69.4±12.3 kg) participated in this study. Their monocular visual acuity tested by Landolt C was 1.0 or higher. The participants' physical characteristics were almost the same as the agematched national standard values [21]. Prior to measurement, the purpose and procedure of this study were explained in detail and informed consent was obtained from them.

Experimental conditions

COP and electrooculograms (EOG) (horizontal and vertical directions) of each participant were measured in parallel under two sets of experimental conditions (Fig. 1). See the section on measurement procedures for more detailed information on the measurements of COP and EOG. In the space-fixed visual target condition (control), participants maintained an upright stance while fixating on a target placed on a screen 1 m in front of their eyes. In this condition, the head of the participant sways in sync with their body sway during an upright standing posture. Thus, while the participants fixate on the visual target, various eye movements (OFR, smooth pursuit, VOR) occur. The OFR is reflexively induced with a short latency by motion in a wide range of visual fields. Smooth pursuit is a voluntary eye movement for pursuing a visual target that is moving slowly. The OFR occurs due to the retinal slip of a wide range of visual fields, including the peripheral visual fields, while smooth pursuit occurs due to a small retinal slip within the central visual field. The VOR also induces a reflexive eye movement for maintaining the stability of eye direction towards a visual target. In this reflexive eye movement, head sway that interrupts the stable gaze is detected, and then the eyes are given a command to cancel the visual motion due to the head sway.

Meanwhile, in the head-fixed visual target condition, participants maintained an upright stance while fixating on a target that was moving on the screen in sync with their head sway. The visual target moving in sync with the participant's head sway was a point produced by a laser pointer set on each participant's head. Because the pointed visual target was constantly positioned straight in front of the participant's face, it was assumed that the participants were not required to perform any eye movements to track the visual target while maintaining an upright standing posture. This can be assumed because OFR, which reflexively occurs by retinal slip in a wide range of participants' peripheral visual fields, is markedly inhibited by the voluntary smooth pursuit in this experimental condition.

Humans have functions that stabilise their head vertically when the head is moved in, for example, vestibular-neck reflex by semicircular canal and otolith inputs. Put simply, eye movements may be suppressed because the participant's neck muscle activities resulting from vestibular-neck reflexes occur due to body sway. To restrict these neck and trunk movements, participants placed headgear on their head, braced their neck with a tight corset and then secured the headgear to their trunk with hook and loop fasteners.

Visual cues were presented over a wide range of the participants' peripheral visual field (outside 20° of visual angle) by setting red tape (2 cm wide) on the white screen. Visual fields here are broadly classified into the central visual field (visual angle ≤2.5°) and the peripheral visual field (visual angle ≥2.5°) from viewpoints of the anatomical and functional differences of the retina [22].

******* Fig. 1 near here *******

Measurement procedures

1) Electrooculogram (EOG) measurements

To assess eye movements in horizontal and vertical directions, EOGs (μV) were collected while maintaining an upright stance and fixating on a visual target. The EOG method can measure all types of eye movements except for intraocular movements [23], and can detect eye movements from central fixation up to 70° with an accuracy under 2° [23, 24]. A tester attached electrodes to the outsides of both eyes, above and below the dominant eye, and at the frontal plane as a ground electrode to measure EOG of horizontal and vertical directions. Dead epithelial cells were rubbed off with an abrasive sandpaper and cleaned with an isopropyl alcohol swab before attaching the electrodes.

After this preparation, a calibration of the EOG was performed by rotating the angle (°) of each participant's eyeballs. The screen was a flat white board (2×3 m) subtending 67° height×90° width of visual angle. A tester set a reference visual target (at 10° above, below, right and left of the centre of fixation) for the calibration on the screen set in front of the participant and asked the participants to put on the above-stated head-neck fixture and to transfer their gaze to 10° right, left, above and below a central view point (0°) without moving their head.

In addition, blinking needed to be prevented from being mixed into and contaminating the EOG (in the vertical direction) as spike signals to properly assess the eye movements' magnitude. Thus, we asked them not to blink during each trial (for 1 min/trial). Even trials with well measured COP data were excluded from further analysis if the spike signal was mixed with EOG data.

2) Center of pressure (COP) measurements

A stabilometer (G5500, Anima, Japan) was used for COP measurements. This device can calculate the COP of vertical loads from the values of three vertical load sensors, which are put on the peak of an isosceles triangle on a level surface. Data were collected at 20.0 Hz and transferred to a personal computer following A/D conversion.

The COP was measured in accordance with the standard procedure of the committee for standardisation of stabilometric methods and presentations [25]. Participants stood on a footprint painted on the stabilometer with their heels together and with their arms hanging loosely by their sides.

Participants practised COP sway measurement once before the experiment. A tester monitored each participant's COP sway trajectory in each trial and started 5 trials of measurements for 1 min after confirming a stable trajectory. Between the three trials, the participants were allowed to rest (in a sitting position) for 1 min to take into consideration the influence of fatigue. If the participant's foot moved from a position marked with a pen on the stabilometer between trials, they were asked to return it to the original position. The mean of trials, except for error data, was used as a representative value for further analysis.

Parameters

To evaluate COP sway characteristics, we used 12 parameters of COP: three parameters of path length, one parameter of sway area, three parameters of the root mean square, three parameters of sway velocity and two parameters of position (Table 1).

To assess eye movements, we used angle time series data (°) converted from the EOG (horizontal and vertical directions) (μV). After subtracting the mean value of the eye movement angle data from values at each sampling point in the respective sequences and a rectifying process, a mean eye movement angle (°) at each sampling point was calculated by dividing the integrated value for 1 min (1 trial) by the total number.

Analysis methods

To test the mean difference of each COP parameter between both experimental conditions, an unpaired t-test was used. As for the mean eye movement angle, two-way ANOVA (eye movement direction: horizontal and vertical directions×experimental condition: space-fixed and head-fixed visual target conditions) for repeated measurements was used.

Tukey's honestly significant difference (HSD) method was used for a multiple comparison test if ANOVA indicated a significant interaction. The level of statistical significance was set at $p<0.05$.

Results

Table 2 shows the test results of two-way ANOVA (eye movement direction × experimental condition) and multiple comparisons for mean eye movement angles. The mean eye movement angle was significantly larger in the vertical direction than in the horizontal direction in both experimental conditions, and was also found to be larger in the spaced-fixed visual target condition than in the head-fixed visual target condition. Table 1 shows the test results for COP parameters between both experimental conditions. No significant difference was found in any COP parameters.

******* Tables 1 and 2 near here *******

Discussion

In the space-fixed visual target condition, participants gazed at a stationary visual target on a screen placed before their eyes. Eye movements therefore occurred due to the participants' own head sway induced by body sway. In contrast, in the head-fixed visual target condition, participants' eye movements were suppressed because the participants fixated on a head-mounted visual target moving in sync with their head sway. It was confirmed that eye movements were suppressed by the head-fixed condition selected in this study but were not entirely inhibited. The mean angles of the eye movement in the horizontal and vertical directions were lower in the head-fixed visual target condition (Table 2). The EOG method, which has a high measurement accuracy [23, 24], has been used to measure almost all types of eye movements [25]. In addition, the tester asked participants not to blink during EOG measurements. It is therefore assumed that the EOG data included few electric potential components other than eye movements induced by focusing on a target. The experimental conditions used in this study seemed to be appropriate to examine the experimental hypothesis.

As a result of the comparison of COP sway parameters measured under both experimental conditions, no difference was found in any parameters between experimental conditions. The above-stated results conflict with our hypothesis that non-visual information, i.e., extraretinal information such as the motor commands sent to the extraocular muscles (efference copy or corollary discharge) [26–28] or the inflow sensory information derived from extraocular muscle proprioceptors [26, 29], contributes to stabilise an upright standing posture. In both the spacefixed and head-fixed conditions used in this study, the task of maintaining a stationary standing upright stance was adopted. As a result, the mean eye movement angle was very small (about 2° in the horizontal direction and about 3° in the vertical direction) while fixating on a visual target fixed in front of the participants' eyes, even in the space-fixed condition. This study used a similar measurement condition to the actual equilibrium test to allow for the practical application of our findings. In such measurement conditions, in which participants maintain an upright standing posture while fixating on a stationary fixed visual target, eye movement caused by the fixation task occurs. Eye movement induces non-visual eye position information that is in addition to retinal information. However, during a static upright standing posture, the amount of eye position information associated with eye movement during fixating may not be sufficient to contribute to postural stabilisation.

When a participant moves both eyes, the position of the image of visual targets in the external world on the retina changes. Therefore, it is impossible to determine the correct position of the visual targets by simply using the position of the image on the retina. Namely, to determine the correct position, information regarding how much and in which direction the eyes moved (eye position information) is necessary [19]. Matin et al. [30] reported that when stupefying extraocular muscles by curare, error in the spatial orientation after eye movement was found. This result suggests that adequate eye position information was not sent to the sensory system due to the stupefaction of the ocular muscles. However, when this experimental trial was conducted in a bright room, the error disappeared. Similar findings were seen in Stark and Bridgeman's [31] report. In this study, there were rich visual cues in addition to the eye position information, because trials of both experimental conditions were conducted in a bright room. Thus, there is a possibility that the consistency of the visual world can be maintained, because the suppressed eye position information in the head-fixed condition was compensated for by such visual information.

There are a few limitations in this study. A visual target moving in sync with the participant's head sway was created by a head-mounted laser pointer. Because this head-mounted visual target was positioned straight in front of the participant' face, it was assumed that eye movement does not occur in this head-fixed visual target condition. However, complete suppression of each participant's eye movements was not achieved. In the head-fixed condition, eye movement was suppressed. Alternatively, the retinal slip in a direction opposite to movement of the visual target moving in sync with participants' head sway on the peripheral visual fields occurs. This retinal slip was also induced in the control condition (space-fixed visual target condition). However, the amount of the retinal slip is larger in the head-fixed condition. This may have a contradictory affect on eye movement suppression. Further study is necessary to investigate the influence of eye movement on postural control.

In conclusion, it was suggested that non-visual eye position information from external eye muscles to the sensory perception system contributes little to postural stabilisation under the measurement conditions used in this study.

Conflict of interest statement

The authors declare that they have no conflict of interest related to the publication of this article.

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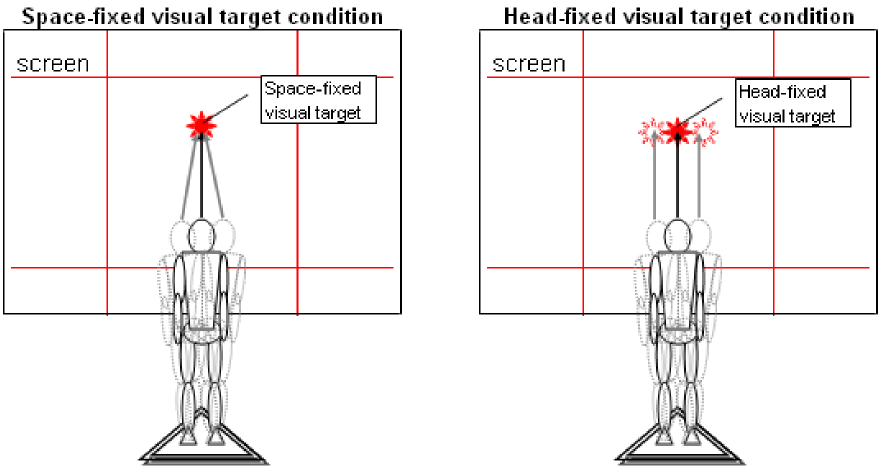
Figure 1



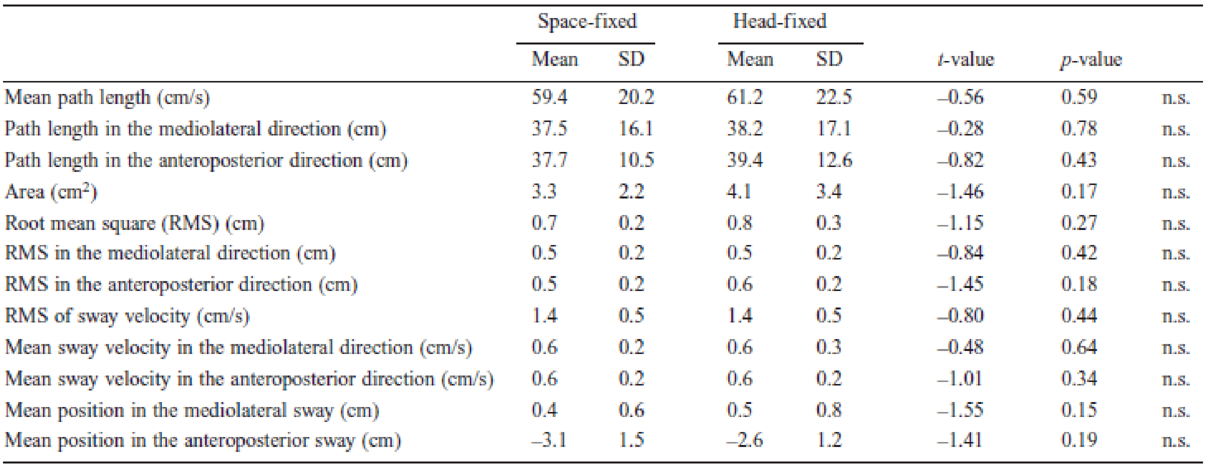
Space-fixed visual target condition

Head-fixed visual target condition

Figure legends

Fig. 1 Schematic view of each experimental condition. In both experimental conditions, participants wore the head-neck fixture consisting of headgear, a neck corset and hook-and-loop fasteners

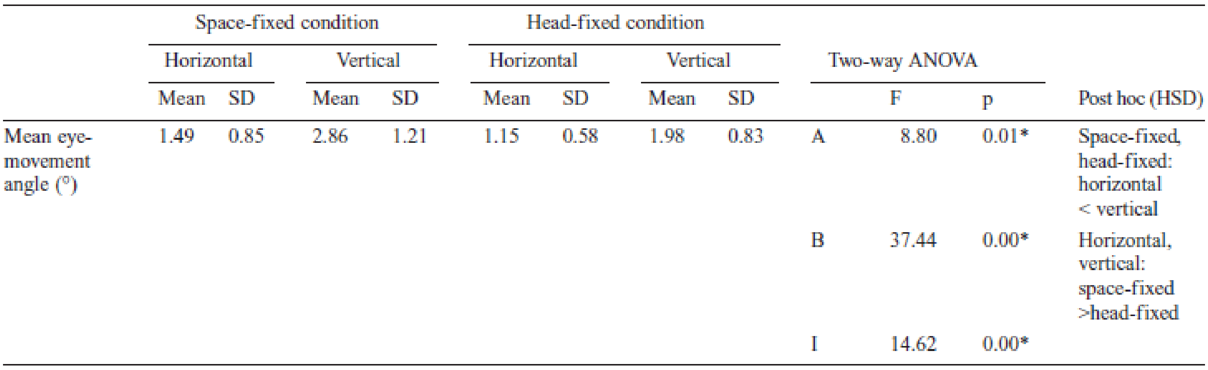
Table 1 Results of paired t-test (n=12)



	Space-fixed		Head-fixed				
	Mean	SD	Mean	SD	*t*-value	*p*-value	
Mean path length (cm/s)	59.4	20.2	61.2	22.5	–0.56	0.59	n.s.
Path length in the mediolateral direction (cm)	37.5	16.1	38.2	17.1	–0.28	0.78	n.s.
Path length in the anteroposterior direction (cm)	37.7	10.5	39.4	12.6	–0.82	0.43	n.s.
Area (cm^2)	3.3	2.2	4.1	3.4	–1.46	0.17	n.s.
Root mean square (RMS) (cm)	0.7	0.2	0.8	0.3	–1.15	0.27	n.s.
RMS in the mediolateral direction (cm)	0.5	0.2	0.5	0.2	–0.84	0.42	n.s.
RMS in the anteroposterior direction (cm)	0.5	0.2	0.6	0.2	–1.45	0.18	n.s.
RMS of sway velocity (cm/s)	1.4	0.5	1.4	0.5	–0.80	0.44	n.s.
Mean sway velocity in the mediolateral direction (cm/s)	0.6	0.2	0.6	0.3	–0.48	0.64	n.s.
Mean sway velocity in the anteroposterior direction (cm/s)	0.6	0.2	0.6	0.2	–1.01	0.34	n.s.
Mean position in the mediolateral sway (cm)	0.4	0.6	0.5	0.8	–1.55	0.15	n.s.
Mean position in the anteroposterior sway (cm)	–3.1	1.5	–2.6	1.2	–1.41	0.19	n.s.

n.s., $p>0.05$

Table 2 Test results for eye-movement angle (n = 12)



	Space-fixed condition				Head-fixed condition				Two-way ANOVA			
	Horizontal		Vertical		Horizontal		Vertical					
	Mean	SD	Mean	SD	Mean	SD	Mean	SD		F	p	Post hoc (HSD)
Mean eye-movement angle (°)	1.49	0.85	2.86	1.21	1.15	0.58	1.98	0.83	A	8.80	0.01*	Space-fixed, head-fixed: horizontal < vertical
									B	37.44	0.00*	Horizontal, vertical: space-fixed >head-fixed
									I	14.62	0.00*	

*p<0.05; A, factor of experimental condition; B, factor of eye-movement direction; I, interaction