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Original Research Article

INFLUENCES OF VISUAL AND PLANTAR SENSORY INFORMATION ON STANDING POSTURAL CONTROL: A COMPARISON BETWEEN VISUALLY IMPAIRED AND SIGHTED INDIVIDUALS

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ABSTRACT

Background: Information from other sensory organs may become more important for the visually impaired individuals. However, very few reports on this type of sensory compensation have been published.

Objectives: This study aimed to investigate the impact of visual information and plantar sensory information on standing postural control by comparing visually impaired and sighted individuals.

Materials and Methods: The study included 22 adult men with no visual impairment (sighted group) and 13 adult men with visual impairment (visually impaired group). We performed Equitest measurements under conditions with 12 possible factors, including visual information (eyes closed, eyes open, and dynamic visual environment), plantar sensory information (with or without a textured sheet placed under the feet), and platform stability (stable or unstable). A three-way analysis of variance was performed.

Results: Significantly higher balance strategy scores were observed in the sighted group than in the visually impaired group, indicating better balance without a textured sheet and on an unstable platform. Latency was significantly shorter in the sighted group than in the visually impaired group. Relative response strength scores were higher in the visually impaired group with the textured sheet and backward shifting platform than in the sighted group, indicating a superior stability.

Conclusion: In postural control without visual information while standing on a surface in motion, plantar information that originated from textured sheets was more effective in assisting balance in visually impaired individuals than in sighted individuals.

KEY WORDS: Postural control, visual impairment, plantar sensations, eyes closed.

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INTRODUCTION

Normal postural control comprises coordination of 1) visual sensory information from the environment, somatosensory, and vestibular systems to provide information regarding physical position and movement; 2) motor activities; and 3) sensory information [1].

In neurophysiology, the latency of muscular response to sway-related signals transmitted by the visual system, which is a sensory pathway, is 200 ms, which is very slow compared with that to signals from the somatosensory system (80–100 ms) [2]. In an experiment on the latency and amplitude of muscular response to stimuli of equal acceleration from the somatosensory and vestibular systems, the response to vestibular signals was a mere 1/10th of that to somatosensory signals [3], indicating that contributions from the vestibular system are significantly smaller than those from the somatosensory system. The somatosensory system plays a dominant role in the mechanisms that underlie the standing postural control in adults and has faster response times.

The somatosensory system comprises tactile and proprioceptive senses. The sole of the foot, which is the only support surface while standing, possesses numerous mechanoreceptors that accumulate plantar sensory information in response to motor execution and situational changes of the body [4,5]. Inputs from mechanoreceptors in the foot and proprioceptors in the crural muscle play extremely important roles in standing postural control, and their importance is widely recognized following studies that artificially manipulated somatosensory information [1,6]. Furthermore, when visual information is blocked, the increase in somatosensory information from the plantar mechanoreceptors reduces body sway, thus serving an important role in postural control [5]. Plantar mechanoreceptors are an important source of information for various motions in the standing position, and plantar mechanoreceptors ultimately receive feedback from the body and floor during movement [2].

In addition to motor planning via the central nervous system, afferent information from the vestibular, visual, tactile, and proprioceptive sensory systems is important in postural maintenance or shifting vertical position [7-13]. Among these, visual information is the most important sensory modality for maintaining standing position [7,8,12,14,15]. Humans are 80% dependent on vision for acquiring information from the external world. We can assume that information from other sensory organs becomes more important for the visually impaired. However, there are very few studies regarding this type of sensory compensation. Therefore, this study compared the influence of visual information and plantar sensory information on standing postural control in visually impaired and sighted individuals. In addition, we observed the recovery responses following disturbances with blocked visual information and examined the influence of visual impairment on standing postural control.

MATERIALS AND METHODS

Subjects: Subjects included 22 adult men with no visual impairment (sighted group) and 13 adult men with visual impairment (visually impaired group). The mean age was 21.9 (SD, 2.0) years in the sighted group and 34.5 (SD, 7.4) years in the visually impaired group.

Subjects in the visually impaired group were weak sighted or completely blind, exercised for ≥3 h/week, working, and commuted to work 5 days a week. Individuals with orthopedic or auditory medical history were excluded from both the groups.

Setting: We used the NeuroCom computerized dynamic posturography (hereinafter, Equitest) to conduct sensory organization tests (SOTs) and motor control tests (MCTs).

As visual information conditions, we used eyes open, eyes closed, and dynamic visual environment (false recognition of visual information), which are set measurement conditions in the Equitest. The plantar sensory information was provided by having subjects stand in two settings with bare feet. Conditions included 1) a platform with a textured sheet (diameter of protrusions: 5 mm, center-to-center distance between protrusions: 10 mm) and fabric on top to keep the protrusions out of sight and 2) a platform without the textured sheet. Each individual first underwent SOTs, followed by MCTs. Measurements with and without the textured sheet were randomly taken, and there was a 10-min interval between sheeted and sheetless trials.

SOT: As shown in Table 1, SOT measurements were recorded under conditions 1–6 by combining visual information, visual surroundings, and the platform. The inclination of the visual surroundings and mobility of the platform follow the subject's body sway. SOT was measured by having the subjects take a standing position on the platform with visual surroundings and testing conditions 1, 2, 3, 4, 5, and 6. As measured in SOT, the equilibrium quotient (EQ) and balance strategy score (BSS) were used to assess postural control ability. EQ and BSS were determined using the device and calculation, as given below.

Table 1: SOT visual and platform conditions.

	Visual information	Foreground surround	Platform
Condition 1	Eyes open	Stable	Stable
Condition 2	Eyes closed	Stable	Stable
Condition 3	False recognition	Unstable	Stable
Condition 4	Eyes open	Stable	Unstable
Condition 5	Eyes closed	Stable	Unstable
Condition 6	False recognition	Unstable	Unstable

EQ is a conversion of stable posture based on the subject's body sway under each SOT condition (20 s/measurement). The maximum score was 100, and values closer to 100 indicated narrow-range body sway. The maximum range was a total of 12.5° (anterior: 6.25°, posterior: 6.25°) in the sagittal plane on the basis of the vertical physical axis in a normal standing position. The maximum and minimum sway angles during the 20-s test[θ max (°) and θmin (°), respectively] were used to obtain the converted score given by the following formula:

[12.5° " (θmax – θmin)/12.5°] × 100

When this value exceeded the anterior and posterior maximum sway angles, a loss of balance was considered, and the subject received a score of 0.

BSS was obtained by the vector of the plantar pressure center along the vertical axis and that of the horizontal shear force on the support surface along the forward–backward axis. The vertical floor reaction force from the ankle joint control was used as the reference. A high BSS indicated a slow shift in the center of gravity. Conversely, a low BSS, which may be caused by horizontal shear force owing to sudden acceleration of the trunk, particularly the hip joint, normally related to sudden flexion–extension movements in the hip joint. Subjects received the maximum score when their ankle strategy completely stabilized posture and a score of 0 when there was no vertical floor reaction force, which was defined as a loss of balance. Measurements were taken in three trials of each condition, and the mean values were used for analysis.

MCT: MCT measures the physical response to a counter disturbance that is caused by a sudden forward or backward horizontal platform shift. There were six conditions for the platform, combining direction of platform movement (forward or backward) and range (small, medium, and large) (Table 2). The order of test conditions for MCT measurements was randomly decided. Horizontal movement perturbation was automatically repeated thrice in each condition. Of the items measured in MCT, latency (ms) and relative response strength (RRS; degree/s) were used.

Table 2: MCT platform conditions.

	Direction of movement	Range of movement
Condition 1	Backward	Small
Condition 2	Backward	Middle
Condition 3	Backward	Large
Condition 4	Forward	Small
Condition 5	Forward	Middle
Condition 6	Forward	Large

Latency is the time between when the support surface begins to shift and the subject begins recovering against the movement. It indicates the rate of change in the plantar center of pressure, occurring beyond a given temporal threshold (ms), and is determined using a computer algorithm. The latency was detected for both the right and left legs.

RRS signifies the floor reaction force of the ankle joint, which the subject used for postural stabilization against the shift in support surface. RRS was calculated from the inclination of the response waveform (degree/s) to determine the amount of force a subject exerted to maintain a standing position against the horizontal shift. A score of 100 points indicated complete utilization of the ankle strategy for postural stabilization, whereas a score of 0 points indicated nonoccurrence of a vertical floor reaction force (a fall). Lower scores indicated a sudden movement in the center of gravity in the hip joint control. Three trials were performed under each condition. RRS values were determined for both the right and left legs and the mean value was used.

Statistical analysis: EQ and BSS of SOT were analyzed using paired repetitive measurement of three-way analysis of variance (ANOVA) and the following three factors: 1) vision (eyes open/eyes closed/swaying surroundings), 2) platform (stable/unstable), and 3) plantar sensation (bare feet/textured sheet) for the sighted group. For the visually impaired group, a paired repetitive measurement of two-way ANOVA was performed under the eyes closed condition using the platform (stable/unstable) and plantar sensation (bare feet/textured sheet) as variables. For the eyes closed condition, a paired three-way ANOVA was performed using the presence/absence of disability (sighted group/visually impaired group), platform (stable/unstable), and plantar sensation (bare feet/textured sheet) as independent variables.

To analyze latency and RRS, we performed a paired three-way ANOVA using the presence/absence of disability (sighted group/visually impaired group), the direction of platform shift (forward/backward), and the plantar sensation (bare feet/textured sheet) as independent variables. If a significant difference was detected in the main effect, we performed a multiple comparison Bonferroni test. We used IBM SPSS Statistics Ver. 22 for statistical analysis. The levels of significance were set at 5%.

Research ethics: This research was approved by the Ethics Committee of the Tokyo Metropolitan University Arakawa Campus (approval number 06070).

RESULTS AND DISCUSSION

SOT: There were three visual conditions in SOT: 1) eyes opened, which allowed access to visual information; 2) eyes closed, which blocked visual information; and 3) false recognition of visual information, which was the result of visual surroundings following the subject's center of gravity. There were four conditions for the platform: 1) horizontal stability, 2) forward–backward platform sway following weight shift, 3) plantar sensory conditions with the textured sheet, and 4) plantar sensory conditions without the textured sheet. We observed postural control responses under combinations of each condition for the sighted and visually impaired groups and made intergroup comparisons. EQ and BSS of the sighted and visually impaired groups are shown in Table 3.

Results of the three-way ANOVA revealed no significant secondary interactions for the sighted group with respect to EQ and BSS. However, the primary interaction was significant under the visual and platform conditions. In the simple main effect test, responses under the visual and platform conditions were significant. Multiple comparisons of the visual conditions revealed that both EQ and BSS were significantly lower under the eyes closed condition than under the eyes open condition and were significantly lower under the dynamic visual environment than under the eyes open condition. Subject stability was higher when the platform condition was stable than when it was unstable, and among all visual conditions, stability was highest un-

Table 3: Results of EQ/BSS and distribution analysis among three factors.

	Visual information		Eyes open		Eyes closed		Unstable		Main effect			Interaction
	Plantar sensory information		Sheetless	Sheeted	Sheetless	Sheeted	Sheetless	Sheeted	Vision	Platform	Plantar sensation	Vision × Platform
Equilibrium quotient (EQ)	Sighted group	Stable	93.14 (2.37)	93.86 (2.66)	91.67 (2.67)	91.42 (3.51)	90.71 (3.72)	90.42 (3.81)	49.10**	158.71**	0.01	20.17**
		Unstable	82.36 (11.04)	83.42 (7.25)	68 (12.56)	71.56 (10.46)	69.86 (13.9)	65.76 (14.17)				
	Visually impaired group	Stable			90.96 (5.95)	91.19 (5.48)				106.04**	0.23	
		Unstable			73.44 (9.97)	74.68 (7.47)						
Balance strategy score (BSS)	Sighted group	Stable	95.1 (1.37)	94.67 (1.46)	94.14 (2.41)	94.1 (1.97)	93.24 (2.6)	93.12 (3.23)	13.97**	215.99**	2.2	5.42**
		Unstable	88.17 (2.79)	86.45 (5.98)	82.45 (4.12)	80.14 (9.18)	82.5 (9.9)	78.5 (14.73)				
	Visually impaired group	Stable			94.15 (1.9)	93.42 (2.47)				124.07**	0.14	
		Unstable			81.29 (6.4)	83.01 (6.05)						

der the eyes open condition.

Two-way ANOVA revealed that the main effect under platform conditions was significant for the visually impaired group, although the interaction was not significant. Stability was also the highest when the platform was stable for the visually impaired group.

In a comparison between the sighted and visually impaired groups, the main effect under platform conditions was significant for EQ ($F = 196.67$, $p < 0.01$). For BSS, the main effects for the presence/absence of disability and platform and plantar sensory conditions were significant, and we observed secondary interactions ($F = 26.95$, $p < 0.01$). In the test for simple interactions, the presence/absence of disability and plantar sensory conditions were significant under the unstable platform condition ($F = 28.13$, $p < 0.01$), and platform condition and presence/absence of disability were significant under the sheetless condition ($F = 114.09$, $p < 0.01$). In the test of the simple and simple main effect, the sighted group was significantly more stable than the visually impaired group under the sheetless/unstable platform condition ($F = 79.64$, $p < 0.01$) (Figure 1).

Fig. 1: Balance strategy scores (BSSs) for the combination of three factors.

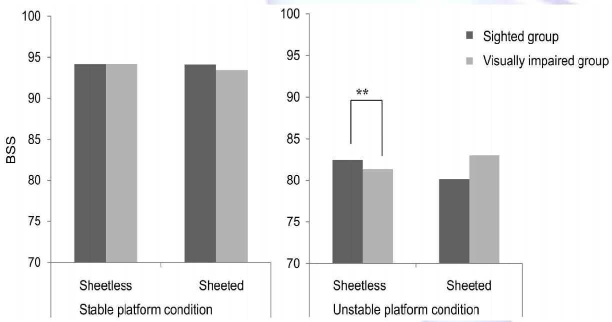
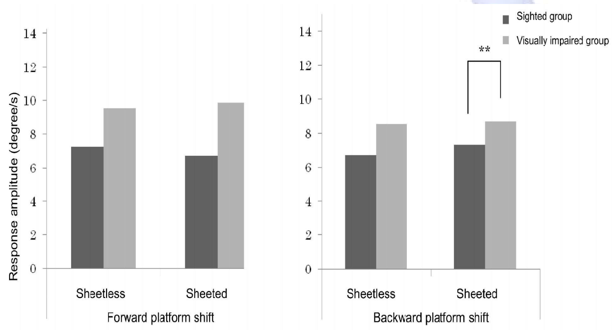


Fig. 2: Results of response amplitude for the combination of three factors.



MCT: For MCT, we tested forward and backward horizontal shift of the platform with eyes closed and with or without the textured sheet on the platform. We compared the response latency to horizontal platform movement disturbances and RRS of both groups under the 2 × 3 = 6 platform conditions, the presence/absence of disability, and plantar sensory conditions. The results for latency and RRS are shown in Table 4. The main effect for the presence/absence of disability was significant for latency ($F = 7.44$, $p = 0.01$); however, the interaction was not significant. For RRS, the main effect of presence/absence of disability was significant, and secondary interactions of platform conditions, presence/absence of disability, and plantar sensory conditions were also significant ($F = 5.05$, $p < 0.05$). A test of simple interaction by factors revealed a significant interaction between platform and plantar sensory conditions in the sighted group ($F = 8.30$, $p < 0.01$) and platform and presence/absence of disability under sheeted conditions ($F = 5.96$, $p < 0.05$). Furthermore, in the test of simple and simple main effect, the scores significantly lower in the sighted group than in the visually impaired group under the sheeted/platform posterior movement condition ($F = 10.23$, $p < 0.01$) (Figure 2). Altogether, these results indicate that the sighted group reacted more rapidly to external provocations than the visually impaired groupÿ demonstrating a dynamic hip joint response.

Table 4: Results of response latency and response amplitude.

		Response latency		Response amplitude	
Direction of platform shift	**Plantar sensation**	**Sighted group**	**Visually impaired group**	**Sighted group**	**Visually impaired group**
Forward	**Sheetless**	118.33 (14.54)	132.82 (13.8)	6.69 (2.42)	8.55 (2.63)
	Sheeted	111.21 (39.64)	130.51 (11.13)	7.3 (3.78)	8.68 (2.36)
Backward	**Sheetless**	116.14 (19.57)	127.56 (9.12)	7.24 (2.64)	9.54 (2.16)
	Sheeted	106.74 (37.89)	129.74 (8.55)	6.71 (3.09)	9.88 (2.34)

Influence of plantar sensory information: Under closed eyes/stable platform conditions, BSS was similar in both the groups, regardless of disability or plantar sensory conditions. Under the unstable platform condition, there was an interaction between disability and plantar sensory conditions. The sighted group had higher scores under the sheetless condition, whereas the visually impaired group had higher scores under the sheeted condition. Higher BSS indicates an ankle strategy, whereas low BSS indicates a hip joint strategy. In the hip joint strategy, a rapid flexion–extension movement of the hip joint is the result of trunk acceleration, and a lower BSS indicates that a dynamic postural control reaction occurred in the sagittal plane. When BSS was compared with plantar sensory information, BSS was low with textured sheet under the stable and unstable platform conditions for the sighted group and under the stable platform condition for the visually impaired group. However, scores in the visually impaired group were higher with the textured sheet only under the unstable platform condition. The sighted group had higher scores under the sheetless unstable platform condition than the visually impaired group. Therefore, the sighted group had a more stable standing posture and more frequently controlled body posture using the ankle, demonstrating that plantar sensory information from the sheet did not affect the balance strategy of the sighted group under the unstable platform condition; conversely, it affected the visually impaired group.

RRS values were higher in the visually impaired group than in the sighted group under the eyes closed condition. Under conditions with the backward shifting platform plus the textured sheet, the visually impaired group had significantly higher scores than the sighted group. As with BSS, low RRS values indicated a hip joint strategy and the occurrence of large postural control responses. From these results, we can assume that sensory information from the textured sheet during postural control under conditions with perturbation stimulus and with eyes closed was more effective in the visually impaired group than in the sighted group.

A study investigating the impact of increased plantar sensory information on standing postural control [5] tested gravitational sway with eyes closed and eyes open using shotgun balls under the feet at distance intervals of 10, 15, and 20 mm. The smaller the distance between the balls, the less difference between the eyes open and eyes closed conditions. Similarly, Sakata [16] applied motor perturbation to healthy adults by placing shotgun balls at distance intervals of 10 or 20 mm and found that the standing posture was more stable with a foot board than without one, a larger proportion of the physical control was done by the ankle joint, and the response time was significantly shorter when shotgun balls under the foot board were spaced at 10-mm intervals than at 20-mm intervals. This suggests that plantar sensory information provided from shotgun balls at 10-mm intervals had a more significant effect on balance strategy in sighted individuals. However, this was not the case in our study that used a textured sheet, having the same 10-mm interval between protrusions. The cylindrical protrusions had a diameter of 5 mm on the upper face and the textured sheet was used with a piece of fabric laid on top. In contrast, the protrusions from the shotgun balls in previous studies were spherical, which may have influenced the information presented to the sole of the foot and affected the motor postural control.

This may only have been effective for the visually impaired group under dynamic conditions because as mentioned in the Introduction, the vestibular system makes a small contribution to postural control during the sudden perturbation of the support surface, and the visual response is slower than the somatosensory response. Therefore, the nervous system primarily depends on somatosensory stimuli. Although children and the elderly are more dependent on visual information, somatosensory information normally plays a role in sighted adults. When somatosensory information deteriorates, the visual or vestibular system can compensate to maintain posture, as long as either or both of them are functioning. Correcting the relative importance of sensory information is known as the sensory reweighting hypothesis and is supported by extensive research that show that as the reliability of vision declines, somatosensory information becomes more important, and when tactile reliability declines, visual input becomes more important. Thus, in cases where visual information is blocked, such as in our study, the importance of plantar information is reweighted, and thus, can be observed more prominently in dynamic rather than static postural control.

Impact of visual impairment: Latency was significantly shorter in the sighted group than in the visually impaired group. Foot pressure response to a disturbance in the forward–backward direction while standing is higher in completely blind individuals than in sighted individuals [17]. These data suggest that the visually impaired group, which does not have the daily dependence on vision that the sighted group does, had a faster response to postural control with eyes closed; however, our results did not support this hypothesis. Although both groups had similar values for static postural control response, the sighted group had a faster dynamic postural control response to disturbance and the dynamic response, and hip joint strategy was demonstrated by RRS. In the sighted group, visual feedback on the association among dynamic exercise, environment, and body was possible because of daily experience. In contrast, the visually impaired group lacked these experiences and was unlikely to select a dynamic balance strategy under conditions in which the surrounding environment cannot be confirmed.

Postural movement strategies are steadily and continuously adjusted, and the ankle strategy is dominant while standing on a stable surface. However, in narrow or unstable environments, such as on foam or a narrow beam, individuals shift to a hip joint strategy. Furthermore, the amplitude of a subject's body sway reduces with repeated disturbances of horizontal floor movement. The former supports the results with the sighted group in an unstable position of disturbance with eyes closed, whereas the latter supports the results with the visually impaired group whose subjects regularly experience disturbances without visual information.

The visually impaired acquire walking skills such as "defense postures" to avoid dangers or injuries and learn methods to determine the body's direction to avoid losing track of their direction. Visually impaired children often drag their feet while walking as a defensive posture, thus becoming accustomed to using the ankle strategy when they are unable to confirm their surrounding environment.

From the perspective of development, Lee et al. [18] described the manner in which the visual system affects postural adjustment in infants and young children more than the vestibular or somatosensory systems. Although the visual system leads and integrates other sensory systems, the somatic senses are dominant as a child develops. Similarly, Foudriat et al. [19] stated that although standing postural control is dominated by vision up to the age of 3, it gradually shifts to somatosensory-dominant control. By the age of 6, the somatosensory-dominant mechanisms that regulate standing postural control are similar to those in adults, suggesting that children understand the association between the floor surface and their feet during their developmental processes. By repeatedly referencing visual feedback to physical situations, children eventually shift to a somatosensory-dominant standing postural control mechanism [1].

Infants with visual impairment demonstrate a clear developmental delay in head control at 2 months of age [20]. In cases of congenital visual impairment or visual impairment appearing in early childhood, the proprioceptive and vestibular systems lack normal correction through vision. We can assume that they lack this correction, as well as the repetition of visual feedback associated with it, throughout development, suggesting that in dynamic balance control, experiences with visual feedback are more effective than those without visual feedback.

There are very few comprehensive studies regarding motor abilities, including physical force, in visually impaired individuals in Japan and overseas. According to Kumagawa [21], the maximum oxygen intake of children in schools for the visually impaired is within ±1 standard deviation of the Japanese average. The maximum oxygen intake of completely blind students who practice sports was within one standard deviation of sighted individuals. Although it is a common belief that completely blind individuals have low levels of physical force, it is not necessarily true. Certain individuals do have lower physical force or motor capacities, but others are equal to or outperform sighted individuals. When we compared the physical force of students attending schools for the visually impaired with those of sighted children, there were almost no morphological differences, and their grip, back, and leg muscle strengths were approximately 80%–90% of sighted children [22].

Furthermore, in a study that tested the leg muscle strength of children aged 6–12 years in schools for the visually impaired, the leg muscle strength of sighted children was significantly higher than that of completely blind children [23]. Lower levels of leg muscle strength in completely blind children may be attributed to factors such as insufficient exercise since infancy or early childhood and overprotection by teachers or parents who excessively worry about their safety. When we observed the development of response time in children attending schools for the visually impaired, there were no differences when compared with sighted children in a test of pushing a button in response to an auditory stimulus. Visually impaired children performed more slowly than sighted children in a test that required them to jump forward in response to an auditory stimulus [24], possibly reflecting the fewer opportunities available for engaging in full-body exercise in daily life.

In a study concerning whether the physical force of children with visual impairment differs between those studying at special schools and those receiving integrated education [23], the authors found that the grip strength and 9-min run test scores were higher in the former than in the latter. "Special schools" refer to schools or programs exclusively for children with disabilities, and "integrated education" refers to a model wherein disabled children are in the same classes as able-bodied children. We believe that the differences in this study reflect the differences in the physical education programs. Although the programs may ensure abundant exercise, visually impaired children may not be able to participate in all programs of an integrated education. Differences in physical strength may be because of the differences in exercise experience.

This study was designed to minimize differences in activity levels between subjects in the sighted and visually impaired groups by selecting visually impaired subjects who worked full-time and who were engaged in regular light exercises. Therefore, subjects' differences in motor experiences during development, particularly dynamic motor experiences during puberty, may have played a differential role. In addition, there were intergroup differences in age between the subjects in our study. Choy et al. [25] studied the influence of age using the BalanceMaster on female subjects and found that age was an influential factor in both eyes open and eyes closed trials under easy conditions. Other studies reported that the tactile and pressure thresholds for sensory perception increase with age [26]. These results indicate that further studies are warranted to eliminate the impact of age on measurements of response speed by excluding factors of muscle force or by incorporating sensory trials.

CONCLUSION

The relative involvements of the three sensory systems—the visual, somatosensory and vestibular systems—in posture control are dependent on various other factors. In postural control without visual information while standing on a surface in motion, plantar information that originated from textured sheets was more effective in assisting balance in visually impaired individuals than in sighted individuals. The age, conditions of the tasks, environment, and learned motor functions shift the emphasis of sensory information; thus, they are used selectively. Advancing our knowledge on the use of sensory information in balance control and its introduction to rehabilitation is essential.

ABBREVIATIONS

ANOVA - Analysis Of Variance
BSS - Balance Strategy Score
EQ - Equilibrium Quotient
MCT - Motor Control Test
RRS - Relative Response Strength
SOT - Sensory Organization Test

Conflicts of interest: None

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