

The Influence of Lower Limb Somatosensory Weighting on Visual Dependency Reduction Following Virtual Reality-Based Optokinetic Stimulation in Healthy Adults

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Abstract

Purpose: This study sets out to investigate the hypothesis that differences in lower-limb somatosensory weighting influence the improvement in visual dependency after single-session optokinetic stimulation (OKS) using virtual reality (VR) in healthy adults. **Methods:** The study population comprised 30 young, healthy adults without musculoskeletal or neurological disorders. Visual dependency was measured pre- and post-OKS using the Romberg ratio (open-eye to closed-eye postural sway ratio). Somatosensory weighting was assessed using sway differences on a foam pad compared to a firm surface, with participants categorized into high somatosensory weighting (HSS) or baseline somatosensory weighting (BSS) groups. The OKS involved wearing VR goggles and viewing rotating visual stimuli for a period of two minutes. **Results:** In the BSS group, the closed-eye postural sway area and velocity significantly decreased post-OKS, along with reductions in Romberg ratios, indicating reduced visual dependency. In contrast, the HSS group showed no significant changes in postural sway or visual dependency metrics post-OKS. **Conclusions:** VR-based OKS effectively reduced visual dependency in individuals with baseline somatosensory weighting but had limited impact on those with high somatosensory weighting due to a ceiling effect. These findings underscore the necessity of considering individual sensory weighting when implementing VR balance training for rehabilitation purposes.

Keywords

Virtual Reality, Somatosensory Weighting, Sensory Reweighting

1. Introduction

The ability to maintain an upright posture while standing results from the integration of information from three sensory systems: somatosensory, visual, and vestibular [1] [2]. This sensory integration facilitates the conversion of sensory inputs into motor responses, thereby enabling the activation of appropriate muscles to maintain static balance under gravitational forces or resist balance disturbances during movement. The three sensory systems exhibit redundancy, and their integration is not merely additive but involves a process known as “sensory reweighting”, which optimizes the contribution of each sensory system in response to environmental changes [3] [4].

For instance, under dim lighting conditions, visual information becomes less reliable for maintaining posture, necessitating greater reliance on somatosensory inputs, which are more dependable in such conditions. Sensory weighting in postural control must constantly adapt to environmental changes and automatically redistribute sensory contributions to achieve optimal stability [5] [6]. A key method for inducing sensory reweighting involves reducing the reliability of incoming sensory information. Visual input can be achieved through optokinetic stimulation (OKS), which involves the presentation of moving visual stimuli. The results of studies conducted to date have demonstrated that exposure to OKS increases postural sway in healthy adults. This, in turn, reduces the reliability of visual information and decreases visual dependency in postural control [7]-[9].

Akizuki *et al.* [10] demonstrated that repetitive exposure to virtual reality (VR)-generated visual distortions, which rendered visual information inaccurate in response to head movements and significantly reduced the Romberg ratio in healthy adults. The Romberg ratio is a metric used to quantify the impact of visual deprivation on balance by comparing postural sway values under eyes-open and eyes-closed conditions [11]. VR-based balance training is a pragmatic intervention that does not require specialized equipment or environments, and its efficacy has recently been reported in healthy adults [10] [12].

However, the impact of VR on reducing visual dependency has not yet considered the role of individual differences in somatosensory reliance. While somatosensory inputs contribute to approximately 70% of postural control while standing, with the vestibular system playing a lesser role in static postural maintenance owing to limited head movement [13], somatosensory contributions may already be maximized in some individuals. This phenomenon, termed the “ceiling effect”, suggests that individuals with a high baseline somatosensory weighting may exhibit limited potential for enhancement through VR interventions aimed at reducing visual dependency. Consequently, the impact of VR on visual dependency may be influenced by the extent of somatosensory weighting in each individual [14].

To effectively apply VR interventions targeting visual dependency in clinical settings, it is essential not only to elucidate their general efficacy but also to identify target populations for these interventions. By identifying the target population,

efficient expansion of VR-based rehabilitation approaches can be achieved. Therefore, the present study sought to investigate whether the degree of lower-limb somatosensory weighting influences changes in visual dependency following a single exposure to VR-based OKS in healthy adults.

2. Methods

2.1. Study Design

The present study included 30 young, healthy adults (20 males and 10 females, age 21 ± 0.9 years, height 166.8 ± 6.6 cm, weight 60.0 ± 9.1 kg). This is the first study to investigate whether the effects of OKS training in VR are related to the degree of sensory weighting in the subjects. Therefore, the participants were healthy young adults who (i) had no lower-limb musculoskeletal disease, (ii) had no lower-limb sensory impairment, (iii) had no lower-limb pain or abnormal skin conditions in the plantar region, (iv) had no other diseases or symptoms related to balance disorders, and (v) had no problems with cognitive function. As the study was conducted using VR, participants with previous experience in VR training or gaming were excluded. Prior to the start of the experiment, the purpose, procedures, and potential risks of the study were thoroughly explained to the participants, and written informed consent was obtained. This study was approved by the Ethics Review Board of Biwako Rehabilitation Professional University [approval number: BR24011].

The visual dependency of the participants was assessed by measuring postural sway during two 30-second quiet standing trials with eyes open and closed. The trials were conducted using a posturography system (Gate View; Aison Co., Ltd.) (pretest). During the trials, the participants were instructed to remain as still as possible while standing barefoot in a closed-leg stance (toes and heels together), with the arms hanging naturally at their sides. For the eyes-open condition, participants were instructed to fixate on a 1 cm \times 1 cm target placed at eye level, 1 m away. To evaluate lower limb somatosensory weighting [13], a foam pad (AIREX Balance Pad, Sakai Medical Co., Ltd.) was placed on the posturography platform, and postural sway during eyes-closed quiet standing was measured under the same conditions as in the pretest.

To reduce visual dependency, participants wore smartphone-based VR goggles (VRG-M02RBK, ELECOM Co., Ltd.) equipped with a smartphone (iPhone SE, Apple Inc.). The smartphone displayed a rotational optokinetic stimulus (OKS) generated using a subjective visual vertical (SVV) application (Kuroda ENT Clinic, Version 2.6), where a black dot rotated clockwise at 60°/s. Participants performed a closed-leg stance task while exposed to OKS for a period of two minutes. Postural sway was reassessed after the VR-based OKS task under the same conditions as the pretest (posttest). Visual dependency was calculated using the Romberg ratio, which was determined by dividing postural sway during the eyes-closed condition by that during the eyes-open condition. From the

sway area, the Romberg ratio A (area: Romberg A) was calculated, and from the trajectory length per unit time, the Romberg ratio V (velocity: Romberg V) was determined.

The degree of lower limb somatosensory weighting was calculated based on the increase in postural sway between the eyes-closed condition on the foam pad and the regular eyes-closed condition during the pretest, divided by the sway in the regular eyes-closed condition [13] [15]. Following previous research [13], increases in sway area (ISA) and sway velocity (ISV) were used as indicators.

Participants with ISV values above the mean + 1 SD (6.67 + 6.0), based on a previous study in healthy male students [13], were considered the high somatosensory weighted (HSS) group, whereas participants with ISV values below the mean were considered the basic somatosensory weighted (BSS) group.

2.2. Statistical Analyses

Independent t-tests were conducted to compare age, height, weight, foot length, pretest sway area, trajectory length, and Romberg ratios (Romberg A and V) between the HSS and BSS groups. Paired t-tests were used within each group to evaluate the pre- and post-OKS task effects on the sway area, trajectory length, and Romberg ratios. Statistical analyses were performed using IBM SPSS Statistics Version 29.0, with the significance level set at $p < 0.05$.

3. Results

No significant differences were found between the HSS and BSS groups in terms of sex, height, weight, or foot size ($P > 0.05$) (Tables 1-2). The pre-measurement balance indices were higher in the BSS group than in the HSS group for eye-closure circumferential area ($p < 0.05$), Romberg A ($p < 0.05$), and Romberg V ($p < 0.05$). No significant differences were found for the other balance indices, that is, eye-opening circumferential area and eye-opening and eye-closing trajectory length per unit time (all $p > 0.05$). When comparing the BSS and HSS groups, the BSS group was significantly more visually dependent than the HSS group at pre-measurement.

The immediate effects of the VR-based OKS task (Table 2) revealed no significant changes in sway area, trajectory length, or Romberg ratio (Romberg A and V) before and after the task in the HSS group ($p > 0.05$).

Conversely, in the BSS group, no significant differences were observed in sway area or trajectory length in the eyes-open condition ($p > 0.05$). However, in the eyes-closed condition, the post-task sway area and trajectory length decreased significantly ($p < 0.05$). Additionally, significant reductions in the Romberg A and V scores were observed after the OKS task ($p < 0.05$).

This shows that in the BSS group, the improvement effect of VR+OKS on visual dependence was high. In contrast, the HSS group showed little improvement in visual acuity after VR + OKS.

Table 1. Comparison between groups by somatosensory weighting: basic items and increased center of gravity sway on foam pads.

	Male to female ratio	Age (years)	Length (cm)	Weight (kg)	Foot length (cm)	ISA	ISV
BSS group	9:6	21.2(0.7)	167.2(6.5)	59.6(9.7)	25.2(1.5)	8.4(4.2)	2.24(1.2)
HSS group	11:4	20.7(1.0)	166.3(6.9)	60.4(8.7)	25.8(1.2)	22.8(10.8)*	4.14(2.4)*

Average (SD), Lower limb somatosensory reliance was quantified by comparing postural sway in eyes-closed conditions on foam vs. firm surfaces, using increased sway area and velocity as metrics. ISA: Increase in sway area, ISV: Increase in sway velocity, BSS group: Base somatic sensory weighting group, HSS group: High somatic sensory weighting group, *: $p < 0.05$ (vs BSS group).

Table 2. Within-group comparison of the center of gravity sway scores and Romberg ratios before and after the VR-based optokinetic stimulation (OKS) interventions.

		Perimeter area: eyes open (cm ²)	Perimeter area: eyes closed (cm ²)	Unit time path length: eyes open (cm)	Unit time path length: eyes open (cm)	Romberg A	Romberg V
BSS group	Pre	1.72(0.8)	2.99(1.7)†	1.34(0.8)	2.36(1.4)	1.74(0.7)†	1.73(0.4)†
	Post	1.64(0.6)	2.12(1.1)*	1.30(0.8)	1.67(1.1)*	1.29(0.5)*	1.34(0.4)*
HSS group	Pre	1.51(0.9)	2.29(0.5)	1.31(0.5)	1.95(1.1)	1.55(0.8)	1.58(0.5)
	Post	1.62(0.6)	2.41(1.2)	1.28(0.8)	1.74(1.4)	1.49(0.6)	1.36(0.7)

Average(SD), BSS group: Base somatic sensory weighting group, HSS group: High somatic sensory weighting group, †: $p < 0.05$ (vs. HSS group)*: $p < 0.05$ (vs. Pre).

4. Discussion

The present study investigated the effect of differences in lower-limb somatosensory weighting on visual dependence using VR in healthy adults. The results demonstrated that in the HSS group with high lower-limb somatosensory weighting, the OKS task using VR had no effect on visual dependence, and no sensory reweighting occurred. Conversely, in the BSS group, which was characterized by lower-limb somatosensory weights within the reference values, OKS using VR led to a substantial reduction in Romberg's ratio, a decline in visual dependence during upright postural control, and the occurrence of sensory reweighting.

Somatosensory weighting and visual dependence play crucial roles in postural control and balance. The existing literature highlights that somatosensory weighting is a dynamic process influenced by factors such as age, muscle fatigue, and sensory deficits. Visual dependency, characterized by an overreliance on visual information for spatial orientation, can be particularly challenging for individuals with vestibular disorders. In this context, VR-based OKS has emerged as a novel approach to address these issues. VR-based OKS offers enhanced control over the visual stimuli, provides immersive experiences, and allows for adaptable interventions. Compared with traditional methods, VR interventions provide greater flexibility in stimulus presentation, enable the creation of complex multisensory environments, and offer the potential for gamification to increase patient engagement. Additionally, VR systems facilitate detailed data collection for the precise tracking of progress. However, while VR shows promise, further research is necessary to fully establish its efficacy

compared to traditional methods and to address considerations such as cost, technological barriers, and potential side effects such as cybersickness. Despite these challenges, VR-based OKS interventions represent an innovative approach with potential advantages over traditional methods, warranting continued investigation and refinement for clinical application.

The BSS group showed a slightly higher Romberg ratio than the HSS group in the preliminary center of gravity sway measurements due to higher values of closed-eye circumferential area and unit time trajectory length than the HSS group and significantly lower values of ISA and ISV, which indicate the degree of somatosensory weighting. However, similar to the HSS group, the BSS group had lower somatosensory weighting and was more visually dependent than the HSS group, despite being young, healthy adults with no motor, sensory, or cognitive problems. However, the pre-measurement Romberg ratios of both groups were within the average for the 20 - 24 age group in Japan (1.59 ± 0.91) [16], and the Romberg ratios were neither so high nor so low as to suggest impairment. The fact that there were no differences in height, foot size, or other individual characteristics between the two groups also means that there was no problem using the Romberg rate calculated from the open- and closed-eye COG values as the basis for the difference in the effect of VR + OKS on sensory weighting between the two groups. In this study, only the BSS group showed improvement in visual dependence with VR + OKS. This may be because the exposure effect of a single exposure to VR + OKS was effective in young, healthy adults with high visual dependence and low somatosensory weighting. In contrast, the HSS group showed no improvement in visual dependence after a single exposure to VR + OKS. This may be due to lower visual dependence in the standing posture and higher somatosensory dependence due to higher ISA and ISV in the HSS group than in the BSS group. These results show that in healthy young adults, even in healthy adults, the improvement effect of VR + OKS on the sensory postural control system during standing varies depending on the degree of prior visual and somatosensory weighting. When somatosensory weighting was low and visual dependence was high, somatosensory weighting increased after the OKS task, suggesting that sensory control adapted accordingly. Conversely, when somatosensory weighting is already high, the inclusion of a task that increases visual dependence does not alter somatosensory reweighting and may have a ceiling effect on the contribution of somatosensory control to upright postural control. Therefore, the effectiveness of VR-based training in reducing visual dependence may depend on the degree of visual and somatosensory dependence in the subject.

To maintain postural control in an upright position, it is hypothesized that the weighting of unreliable visual input should be reduced, and the weighting of the somatosensory and vestibular systems should be increased. The somatosensory system is ordinarily responsible for estimating the relative spatial positional relationship between the body and ground, whereas the vestibular sense is informed by the acceleration applied to the head, resulting in a low contribution to static

standing [13]. Consequently, we hypothesized that the observed reduction in visual dependence in the OKS VR group was attributable to enhanced somatosensory weighting.

In contrast, the OKS task with VR had no effect on visual dependence in the HSS group. This can be attributed, at least in part, to the fact that the intermodal effect of the sway of the visual system on the somatosensory system (the effect of weighting other senses) is smaller than the intermodal effect of the somatosensory system on the visual system. The somatosensory system contributes substantially to upright postural control, indicating that its effects are constrained [14]. Consequently, augmentation of the somatosensory system's contribution, which is already substantial, is anticipated to be more modest when the reliability of the visual input is diminished owing to visual system instability. Consequently, within the HSS group investigated in this study, even in the event of a decline in visual reliability during OKS, the ceiling effect of somatosensory weighting did not result in any alteration in visual dependence. Consequently, the reweighting of sensory weighting in the visual input is likely influenced by the subject's dependence on the somatosensory system.

Somatosensory weighting and visual dependence play crucial roles in postural control and balance. Research has shown that force field adaptation is associated with an increase in the brain's weighting of vision versus proprioception [17]. This suggests that the central nervous system dynamically adjusts sensory contributions to maintain an upright stance.

Visual dependency or overreliance on visual information for spatial orientation can affect balance. One study found that visually dependent older adults exhibited greater postural sway in scenarios in which visual and proprioceptive inputs were altered simultaneously [18]. However, visual dependence may not necessarily increase with age but rather affect balance under specific sensory conditions.

Recent studies have explored the effects of balance training using visual input manipulation provided by VR. A study comparing VR-based balance training with conventional methods found that participants in the VR group showed reduced reliance on visual information for balance control [19]. This was evidenced by improved performance in tasks in which visual information was unreliable or absent.

The novelty of VR-based OKS interventions lies in their ability to induce sensory conflict by decoupling visual feedback from vestibular and somatosensory inputs. This approach allows for more precise manipulation of sensory inputs than traditional balance training methods, which typically offer binary visual inputs (eyes open or closed).

The subjects in this study were exposed to OKS using a cost-effective combination of VR goggles and a smartphone application, which is a simple method for use in clinical practice, as opposed to the more expensive head-mounted display. OKS in VR, which can be performed in the absence of a specialized environment, holds potential for application in the rehabilitation of visually dependent balance and vestibular disorders. The results of this study suggest that OKS using VR gog-

gles or HMDs, as well as entertainment, such as video viewing and games, can be used effectively for balance rehabilitation, considering somatosensory weighting. However, given that these studies were predominantly conducted on healthy adults, there is a risk of balance loss after the OKS task in VR owing to changes in the somatosensory system with age and a decrease in visual dependence when used with elderly people with increased visual dependence. Consequently, for effective social implementation, it is imperative to consider not only healthy adults but also elderly individuals and individuals with various diseases, taking sensory dependency into account.

This study has several limitations regarding the clinical adaptation of OKS using VR. First, the study was conducted on healthy young adults; older adults and subjects with balance disorders were excluded from the study. Therefore, studies involving a wider range of participants are required. Second, this study investigated the effects of a single exposure to OKS but did not investigate the long-term effects or adaptation to sensory reweighting. Therefore, a longitudinal approach with repeated exposure is required to investigate the long-term effects.

This study investigated the impact of lower-limb somatosensory weighting on the enhancement of visual dependence before and after a single exposure to OKS using VR. The findings of this study revealed the absence of improvement in visual dependence in the group with higher somatosensory weighting. This finding contributes to the clarification of the target of VR balance training in future rehabilitation of those requiring postural control, thereby promoting its utilization.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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