https://doi.org/10.31871/IJNTR.9.9.8
International Journal of New Technology and Research (IJNTR)
ISSN: 2454-4116, Volume-9, Issue-9, September 2023 Pages 21-27

Influence of a Virtual Environment Presented Using a Head-Mounted Display on the Static Standing Position on an Unstable Support Surface

Norio Kato, Toshiaki Tanaka

***Abstract*—In recent years, virtual reality (VR) has been used in postural control training; however, its effects on postural control have not yet been elucidated. This study aimed to examine the effect of maintaining a stationary standing position in a virtual space presented using a head-mounted display (HMD). Computer graphics were used to create an environment identical to the real-time space and were presented to 11 participants through an HMD. The center of pressure (COP) sway was measured while the participants maintained a stationary standing position on an unstable support surface in real-time and virtual spaces for 30 s. With the participants' eyes closed, the rate of change in COP sway during eye opening was determined. A significant increase in total trajectory length, forward and backward movement speeds, and average movement speed in the virtual space compared with the real-time space was observed. We believe that the increased instability is due to the depth information simulated in the virtual space compared with the real-time space.**

***Index Terms*—VR, postural control, Center of Pressure (COP), Head-Mounted Display (HMD).**

I. Introduction

The world's population aged 65 years and above is increasing yearly, and rapid increase is expected in the coming years [1]. Healthcare costs are also increasing with the increasing aged population [2]. One factor that contributes to the increase in healthcare costs among the elderly is falls [3]. Falls can cause fractures, activity limitations due to fear, reduced quality of life, and death in the elderly [4]-[6].

Postural control in maintaining stability requires complex interactions between the musculoskeletal and nervous systems [7]. However, age-related degenerative changes increase fall risk.

Mehta et al. investigated visual function as a risk factor for falls in the elderly [8]. They interviewed 166 elderly patients about their history of falls in the past 2 months and measured their visual function, including visual acuity, contrast sensitivity, and stereoscopic function. They reported a 3.5-fold increase in the risk of falling when visual function was impaired and a 3.4-fold increase in risk when stereoscopic function deteriorated. Various interventions are being implemented to lower the risk of falls associated with age-related decline in physical function [9], [10]. Recently, virtual reality (VR) is being used for balance training, and its effectiveness has been reported [11]-[15]. The advantages of using VR include cost-effectiveness [16], adjustment of variables important for rehabilitation, such as difficulty and motivation [17], [18], and real-time interactive multisensory interaction [19], [20]. However, one of its challenges is that it is not completely identical to information obtained from real-time space. For example, Renner et al. reported a tendency to underestimate distance recognition in the VR space compared with real time [21]. Postural stability is maintained by the integration of inputs from three sensory sources including visual, somatosensory, and proprioceptive sources [22]. Therefore, postural control in the VR space may differ from that in real time.

Several studies have assessed the differences in postural control between VR and real-time spaces. Horlings et al. examined differences in body sway in real-time and virtual spaces by change the postures and support surfaces [23]. The results showed that body movements increased in the VR space when a landscape that differs from the real-time space was presented using VR glasses. However, they did not find any difference in body movements during eye closure and VR, suggesting that the instability of visual information may be compensated by other senses. Almadjid et al. performed the Timed Up and Go Test in real-time and VR spaces to verify the effect of wearing a head-mounted display (HMD) on dynamic balance [24]. The results showed differences in angular velocity, cadence, and execution time of the trunk. Morel et al. examined the differences in avoidance behavior in real-time and augmented reality (AR) spaces [25]. The results showed that ARs have delayed reactions, resulting in excessive avoidance behavior. These studies suggest that postural instability is likely to increase in VR environments, but the effect of VR on postural control has not been quantitatively verified in an environment similar to real-time space that is reproduced in VR.

The depth information in VR spaces, such as using an HMD, differs from that in real time. Therefore, posture stability in the virtual space is expected to reduce. In a previous study, the authors reproduced an environment similar to real-time space using computer graphics, measured reaching movements to a target in real-time space and VR using an HMD, and quantitatively analyzed the differences. The results showed that reaching movements in the real-time space were significantly smoother than those in the virtual

Norio Kato, Department of Physical Therapy, Faculty of Health Sciences, Hokkaido University of Science, Sapporo, Hokkaido, Japan
Toshiaki Tanaka, Institute of Gerontology, The University of Tokyo, Tokyo, Japan, and Department of Physical Therapy, Faculty of Health Sciences, Hokkaido University of Science, Sapporo, Hokkaido, Japan

space [26]. The reason for this was attributed to be the difference in the depth information obtained. The same may be true for vision-related postural control. Therefore, this study aimed to quantitatively analyze the effects of a VR space of the same quality as a real-time space, presented using an HMD based on COP fluctuations, on postural control during stationary standing. We focused on postural control on an unstable support surface and examined the effects of disrupting the somatosensory input. This study hypothesized that postural stability will reduce in virtual environments, where depth information is inferior to that in real-time environments.

II. MATERIALS AND METHODS

A. Participants

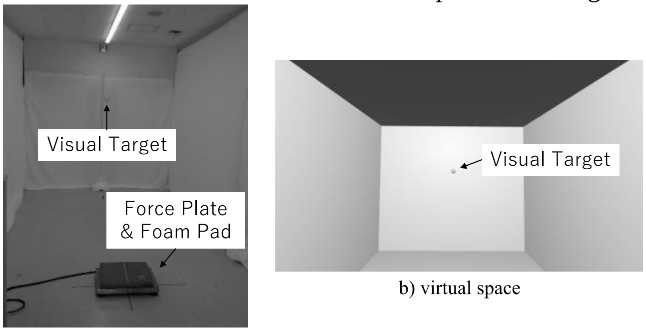
Eleven young adults without orthopedic or neurological disorders participated in this study (ten men and one woman, mean age±standard deviation: 21.7±0.5 years). The participants received no monetary compensation for their participation. They all had normal or corrected-to-normal vision. Those with corrected vision used glasses or contact lenses. Patients with a history of musculoskeletal or central nervous system disorders that could affect postural control were excluded from the study. In addition, those who had difficulty wearing the HMD due to the use of glasses in their daily lives were excluded. All the protocols for this study were approved by the Ethics Committee of Hokkaido University of Science (Review No. 582). Informed consent was obtained from all the participants in accordance with the 1964 Declaration of Helsinki.

B. Equipment and Environment

Fig. 1-a shows the measurement environment in real time. Measurements were performed in a quiet space (6.0 m long × 4.0 m wide × 6.0 m high) covered with white cloth in front and on the sides. A force plate (Stabilometer C-1425; Kyowa Inc., Tokyo, Japan) was placed 5.0 m from the front fabric at the midpoint of the left and right sides to measure coordination of the center of pressure (COP) in the anteroposterior and lateral directions during static standing. COP data were recorded at a sampling frequency of 1000 Hz (Taneda). A foam pad with a thickness of 6.5 cm (AMB-ELETE; Airex AG, Switzerland) was placed on the force plate to increase postural instability [27]. A yellow sponge ball (7.0 cm diameter) was placed in front of the participant as a visual cue. The indicators were presented either 1.5 m or 3.0 m in front of the participants, and the height of the indicators was at the eye level of each participant. The virtual environment was a real-time experimental space reproduced using the Unity software (Editor version 2020.3.26f1; Unity Technologies, San Francisco, CA, USA) and computer graphics (Fig. 1-b). An HMD (VIVE Pro; HTC Inc., New Taipei City, Taiwan) was used to present the VR environment. The device had two 3.5-inch (diagonal) active-matrix organic light-emitting diode (AMOLED) with a resolution of 1440 × 1600 pixels per eye and refresh rate of 90 Hz. The field-of-view of the HMD under optimal conditions was 110°.

C. Procedure

The participants' COP during stationary standing were measured in real-time and virtual spaces. During the measurement, the participant stood on a foam pad with the medial part of both feet in contact with each other and the upper limbs crossed in front of the chest (Fig. 2). The participants were instructed to minimize body sway during the measurement and to keep their eyes on the visual target in front of them. The participants were placed in the measurement position while wearing the HMD for VR



a) real-time space

b) virtual space

Fig. 1. Experimental environment.

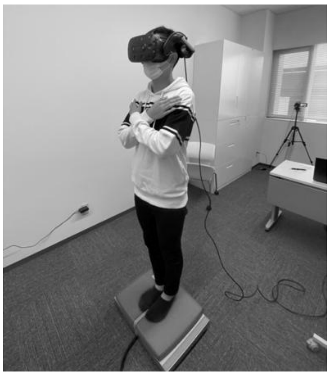


Fig. 2 Experimental posture.

In the virtual space condition, measurements were taken with the head-mounted display attached.

Table 1. Parameters used in the analysis.

COP parameters
total trajectory length [mm]
maximum amplitude (ML direction) [mm]
maximum amplitude (AP direction) [mm]
SD of amplitude (ML direction) [mm]
SD of amplitude (AP direction) [mm]
rectangular area [mm^2]
mean velocity [mm/s]
maximum velocity [mm/s]
maximum velocity (right direction) [mm/s]
maximum velocity (left direction) [mm/s]
maximum velocity (anterior direction) [mm/s]
maximum velocity (posterior direction) [mm/s]
SD of velocity [mm/s]
SD of velocity (ML direction) [mm/s]
SD of velocity (AP direction) [mm/s]

ML: medioraletal
AP: anteriopposterior
SD: standard deviation

measurements. Before these VR measurements, the participants were given time to familiarize themselves with the virtual environment by viewing a spatial image that was different from that of the experimental space.

III. Results

The results of this study are presented in Table 2. The main effects of spatial condition were observed for total trajectory length ($F_{1, 10}$= 8.919, p=0.014, η_p^2= 0.471), average speed ($F_{1, 10}$= 8.947, p=0.014, η_p^2= 0.472), maximum speed (anterior direction: $F_{1, 10}$= 6.606, p=0.028, η_p^2= 0.398; posterior direction: $F_{1, 10}$= 15.214, p=0.003, η_p^2= 0.603), speed standard deviation ($F_{1, 10}$= 12.611, p=0.005, η_p^2= 0.558), and speed standard deviation in the anteroposterior direction ($F_{1, 10}$= 16.745, p=0.002, η_p^2= 0.626). In both cases, instability

Table 2. Comparison of COP parameters measured in two spatial and three visual conditions.

COP Parameters	Real-Time Space			Virtual Space			2way repeated measure ANOVA (p-value)		
	EO/EC	EO1.5/EC	EO3.0/EC	EO/EC	EO1.5/EC	EO3.0/EC	Space	Visual	Space × Visual
total trajectory length	0.60±0.16	0.54±0.16	0.61±0.18	0.74±0.13	0.69±0.12	0.72±0.19	0.014	0.077	0.732
maximum amplitude (ML direction)	0.84±0.35	0.64±0.13	0.84±0.28	0.85±0.24	0.79±0.20	0.86±0.41	0.318	0.091	0.308
maximum amplitude (AP direction)	0.74±0.26	0.80±0.23	0.91±0.30	0.83±0.26	0.90±0.30	0.92±0.38	0.424	0.077	0.693
SD of amplitude (ML direction)	0.84±0.29	0.62±0.09	0.90±0.30	0.85±0.21	0.81±0.22	0.85±0.31	0.412	0.017	0.050
SD of amplitude (AP direction)	0.82±0.31	0.95±0.21	1.13±0.41	0.88±0.17	0.97±0.28	0.94±0.26	0.509	0.027	0.114
rectangular area	0.68±0.47	0.52±0.22	0.81±0.44	0.75±0.48	0.72±0.36	0.92±0.97	0.368	0.105	0.644
mean velocity	0.60±0.16	0.54±0.16	0.61±0.18	0.74±0.13	0.69±0.12	0.72±0.19	0.014	0.077	0.723
maximum velocity	0.53±0.44	0.42±0.32	0.42±0.30	0.66±0.24	0.65±0.29	0.65±0.29	0.084	0.601	0.792
maximum velocity (right direction)	0.72±0.56	0.54±0.33	0.56±0.28	0.70±0.30	0.60±0.19	0.55±0.19	0.886	0.063	0.833
maximum velocity (left direction)	0.71±0.82	0.41±0.22	0.45±0.28	0.78±0.26	0.81±0.30	0.76±0.49	0.099	0.295	0.317
maximum velocity (anterior direction)	0.44±0.21	0.52±0.40	0.49±0.33	0.84±0.56	0.81±0.51	0.91±0.68	0.028	0.821	0.776
maximum velocity (posterior direction)	0.47±0.24	0.36±0.19	0.36±0.16	0.75±0.49	0.75±0.30	0.82±0.56	0.003	0.684	0.541
SD of velocity	0.54±0.12	0.48±0.13	0.56±0.16	0.74±0.16	0.69±0.15	0.73±0.28	0.005	0.130	0.111
SD of velocity (ML direction)	0.65±0.16	0.57±0.15	0.66±0.19	0.75±0.14	0.68±0.12	0.71±0.21	0.092	0.008	0.443
SD of velocity (AP direction)	0.54±0.15	0.51±0.17	0.55±0.17	0.73±0.15	0.69±0.13	0.73±0.21	0.002	0.265	0.974

EC: eyes closed, EO: eyes opened, EO1.5: eyes opened + visual target 1.5m, EO3.0: eyes opened + visual target 1.5m
Mean (SD) is given for each parameter.

For each participant's data, the mean and standard deviations were obtained by calculating the ratios for the eyes opened, eyes opened + visual target 1.5 m, and eyes opened + visual target 3.0 m conditions, based on the values measured with eyes closed in each space.

The influence of two factors on postural control were examined. One was the spatial condition (real-time and virtual environments), and the other was the visual condition (eyes closed, eyes opened with no index, eyes opened with index placed 1.5 m in front of the participant, and eyes opened with index placed 3.0 m in front of the participant). By combining these factors, the measurements were performed in eight conditions. The order of measurements was fixed for all participants as follows: one measurement each in real-time space with eyes closed, eyes opened, eyes opened with index placed 1.5 m in front of participants, and eyes opened with index placed 3.0 m in front of participants, followed by one measurement in the virtual space in the same order of visual conditions. The COP during stationary standing was measured for 30 s.

D. Data and Statistical Analysis

The data measured by the force plate were recorded on a personal computer using an A/D converter (Balance Training Control Unit C-1415; Kyowa Inc., Tokyo, Japan). The measured data on 15 parameters (Table 1) were analyzed using software (Kyowa Inc., Tokyo, Japan) equipped with a force plate. The rate of change in visual conditions was determined in the real-time and virtual space conditions using the closed-eye condition as reference.

SPSS software (version 28; IBM, Chicago, IL, USA) was used for statistical analysis. A multiple-measures two-way analysis of variance was performed for each parameter. When significant differences were observed, the Bonferroni post-hoc method was applied for multiple comparisons. The significance level was set at p = 0.05.

increased in the virtual space compared with that observed in the real-time space (Fig. 3).

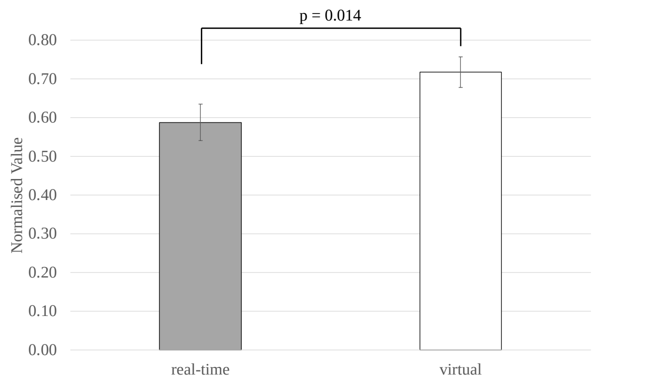
The main effects of the visual condition were significantly different between the spaces for amplitude standard deviation (mediolateral direction: $F_{2, 20}$= 4.998, p=0.017, η_p^2= 0.333; anteroposterior direction: $F_{2, 20}$= 4.344, p=0.027, η_p^2= 0.303) and velocity standard deviation (mediolateral direction: $F_{2, 20}$=6.198, p=0.008, η_p^2= 0.383). The velocity standard deviation in the mediolateral direction was more stable in the 1.5 m visibility condition than in the open-eye condition and in the 1.5 m visibility condition than in the 3.0 m visibility condition. Regarding the amplitude standard deviation in the anteroposterior direction, more stability was observed in the open-eye condition than in the 3.0 m visual field condition. The multiple comparisons test showed no significant differences in the amplitude standard deviations in the mediolateral direction (Fig. 4).

No interaction between the spatial and visual conditions was observed.

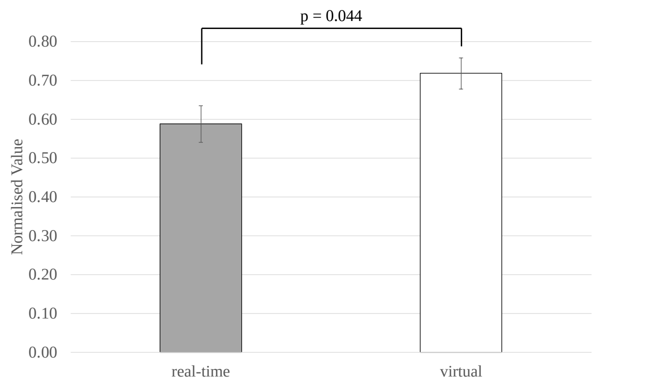
IV. Discussions

This study examined the effect of virtual space presentation on postural control by comparing parameters related to COP variability when the participants were asked to maintain a stationary standing position on an unstable support surface in real-time and virtual spaces. For the virtual space, an environment similar to real-time space was constructed using computer graphics and presented using an HMD. The results showed significant differences in the total trajectory length and movement velocity of the COP, especially in the parameters related to forward and backward movement speeds, indicating that instability is enhanced in the virtual space.

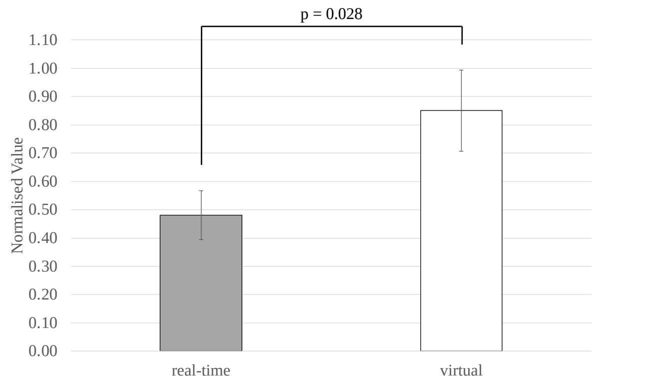
The results obtained in the virtual condition suggested an increase in instability with respect to the anteroposterior component of the mean COP velocity. No significant differences were found between the real-time and virtual spaces in the mediolateral component. One reason may be the difference in depth information between the two spaces. Humans use two factors including psychological and physiological factors, to perceive the depth of space [28], [29]. Psychological factors, which are used to represent depth in two-dimensional planes, such as paintings and televisions, include perspective, shading, skin texture gradient, and motion parallax. Physiological factors include binocular disparity, adjustment, and convergence. In a 3-D space, both psychological and physiological factors are considered. We examined the effects of the differences in these two factors on behavior. Using 2-D and 3-D displays, the effects of differences in depth information on the reaching motion of a target displayed in a virtual space were verified [30]. The results showed that the smoothness of the reaching motion decreased and the execution time increased in the 2-D VR display owing to the effect of depth perception in the anteroposterior direction. In addition, the authors reported a decrease in smoothness in the virtual space when younger participants were asked to reach out to a target placed at the same distance as that in the real-time space [26]. Both studies showed that the reduced operation performance in the VR space was due to the depth information. Renner *et al.* also reported a tendency to underestimate distance recognition in VR spaces compared with real-time space [21]. The HMD



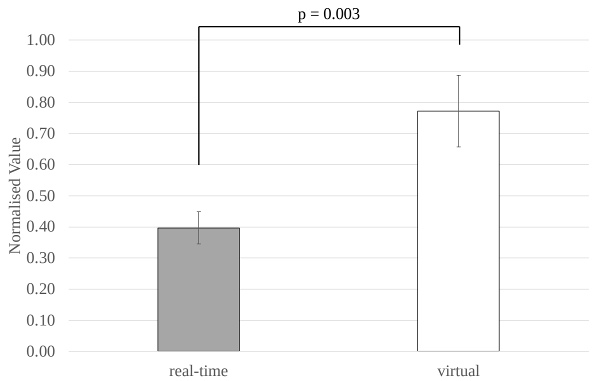
a) total trajectory length



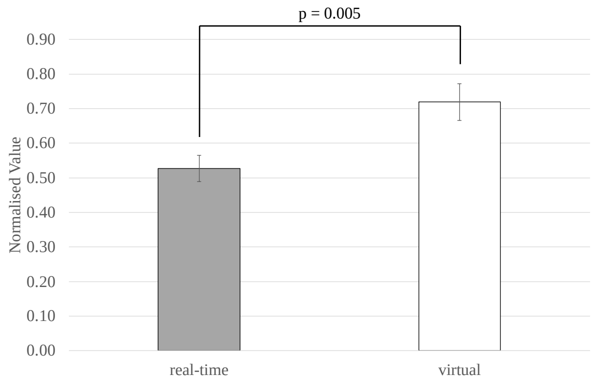
b) mean velocity



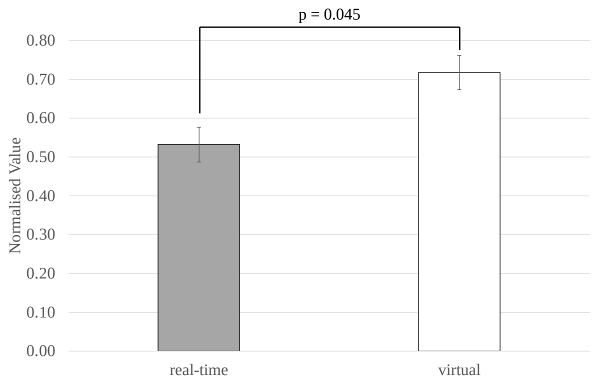
c) maximum velocity (anterior direction)



d) maximum velocity (posterior direction)



e) SD of velocity

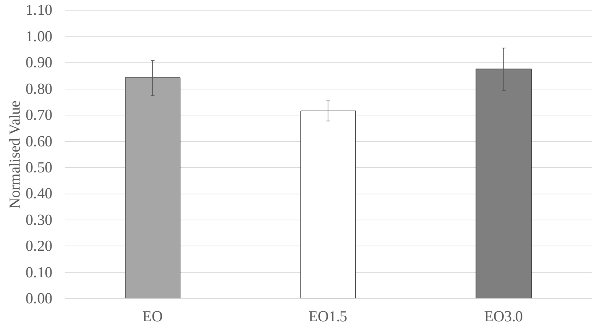


f) SD of velocity (anteroposterior direction)

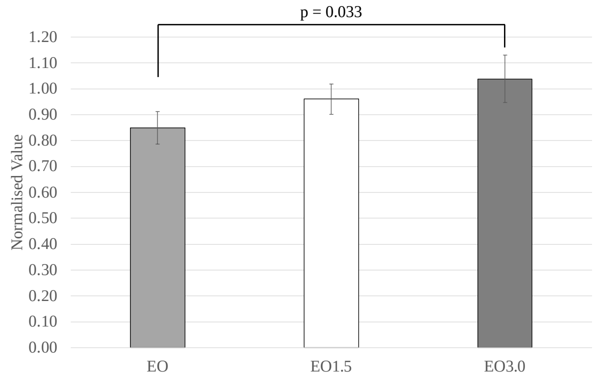
Fig. 3 Multiple comparison tests results in spatial conditions.

https://doi.org/10.31871/IJNTR.9.9.8
International Journal of New Technology and Research (IJNTR)
ISSN: 2454-4116, Volume-9, Issue-9, September 2023 Pages 21-27

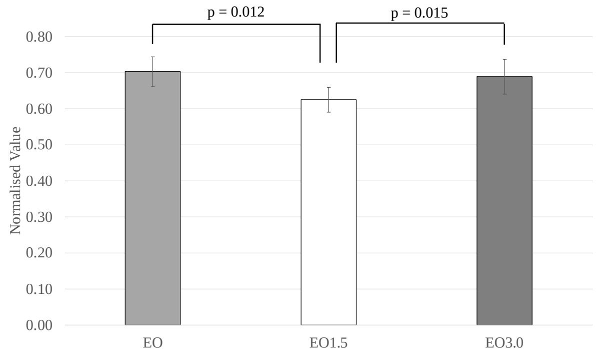
used in this study presented images to the left and right eyes considering binocular disparity. However, because the position of the display built into the HMD is fixed, the depth information obtained from the convergence angle differed from that in the real-time space. In this study, the visual information obtained through the HMD did not accurately determine the distance to the visual targets, which may be the cause of the increased average COP velocity in the virtual space. The soft foam used in this study disrupted somatosensory perception, which is predicted to increase reliance on vision as a source of information about body motion. Pieto *et al.* compared parameters related to COP during stationary standing between older and younger patients and reported that the older group had significantly larger mean COP velocity and mean COP velocity of the anteroposterior components [31]. They reported that this was due to age-related degeneration, which results in decrease in visual function. Lord *et al*. measured center of gravity sway during 30 s of stationary standing and performed visual function tests (visual acuity, contrast sensitivity, depth perception, stereoacuity, and lower visual field), and assessed quadriceps muscle strength, intrinsic sensation, and reaction time in 156 older adults [32]. The results showed a relationship between visual function, quadriceps muscle strength, and reaction time during stationary standing on an unstable support surface. Furthermore, when the total trajectory length of the center of gravity sway was used as the dependent variable, contrast sensitivity, stereopsis, and quadriceps muscle strength were significant independent variables. These results were consistent with those of the present study. We assumed that the distance between the participants and the visual targets was misperceived in the virtual environment and that the COP velocity from the visual information to the recognition of body motion increased.



a) SD of amplitude (mediolateral direction)



b) SD of amplitude (anteroposterior direction)



c) SD of Velocity (mediolateral direction)

Fig. 4 Results of multiple comparison tests in visual conditions.
(EO: eyes closed, EO1.5: eyes opened + visual target 1.5 m, EO3.0: eyes opened + visual target 3.0 m)

One possible reason for the increased instability in virtual space is the use of HMDs. Information obtained from both central and peripheral visions is important for postural control [27]. In this measurement environment, the HMD's viewing angle was limited to 110°, so there is a possibility that little information was obtained from the peripheral field of view. On the other hand, the only parameters related to the mediolateral direction of the COP that showed significant differences were visual conditions related to the presence and position of the visual target, with no main effect of spatial conditions. This may be due to the difference in the visual information important for body movements in the anteroposterior and mediolateral directions. Bronstein *et al.* stated that absolute motion parallax, i.e., when one moves to the right, the surrounding environment moves to the left, is used for mediolateral posture control [33]. In this study, mediolateral displacement was assumed to be controlled by this absolute motion parallax. This is expected to reduce the influence of the virtual space on mediolateral postural control. However, since no objects other than the visual targets were used in this study, the information obtained from the peripheral vision may have been less. Further verification of these findings is required in the future.

This study has four limitations. The first is the number and age range of the participants. Since the number of participants was 11, further analysis including more participants with a broad age range is needed. The second limitation is the reproducibility of the real-time space. It is possible that the performance of the HMD and the precision of the computer graphics may cause differences in the contrast of the target and other factors. In addition, the viewing angle of the HMD is limited compared with that of the real-time space. Therefore, it is necessary to further verify the effect of VR on postural control using an HMD that can present high-resolution images with a wider field view. The third was the measurement time of COP deviation during stationary standing. Since this measurement was performed during the COVID-19 epidemic, the experimental time was kept as short as possible to prevent infections, but in the future, measurements will be performed at the recommended 120 s [34]. Fourth, we were unable to verify the degree of dependence on visual, somatosensory, and vestibular senses. In this study, the effects of VR on postural control were examined using various parameters related to COP deviation during static standing. However, the changes in the dependence on the three senses has not yet been verified. In the future, the measured COP coordinate data will be subjected to frequency analysis to verify the difference in the dependence on each sense in the two spaces.

In this study, we measured the COP deviation during static standing in real-time and virtual spaces and verified the influence of VR on postural control. We created a virtual space condition that was space similar to a real-time space using computer graphics and presented using an HMD. The results showed that postural instability increased in the virtual space. This could have been because depth information in the virtual space differs from that in real-time space.

V. Conclusions

As VR can create various environments and include game elements, it will be widely used in rehabilitation in the future. In addition, the COVID-19 epidemic has led to the provision of medical services over the Internet, and telerehabilitation is expected to spread widely. Therefore, the effects of VR on humans must be thoroughly verified. As the physical, sensory, and cognitive functions of the elderly and people with disabilities deteriorate with age, it is necessary for the risks associated with the use of VR to be understood in advance. This will ensure the safe and effective use of VR in rehabilitation. More studies are needed to examine the impact of VR from various perspectives.

References

[1] United Nations. *World Population Prospects 2022: Summary of Results*. New York: United Nations, 2022.

[2] C. Normand, G. A. Williams, and J. Cylus. *The implications of population ageing for health financing in the Western Pacific Region: exploring future scenarios and policy options for selected countries using the PASH simulator*. Geneva: WHO, 2022.

[3] J. A. Stevens, P. S. Corso, E. A. Finkelstein, and T. R. Miller. (2006, October). The costs of fatal and non-fatal falls among older adults. *Inj Prev*. [online]. *12(3)* pp. 290-295. Available: https://pubmed.ncbi.nlm.nih.gov/17018668/

[4] A. V. Schwartz, M. C. Nevitt, B. W. Brown, Jr., and J. L. Kelsey. (2005, January). Increased falling as a risk factor for fracture among older women: the study of osteoporotic fractures. *Am J Epidemiol*. [Online]. *161(2)*. pp. 180-185. Available: https://pubmed.ncbi.nlm.nih.gov/15632268/

[5] M. C. Lohman, A. J. Sonnega, E. J. Nicklett, L. Estenson, and A. N. Leggett. (2019, August). Comparing estimates of fall-related mortality incidence among older adults in the United States. *J Gerontol A Biol Sci Med Sci*. [Online]. *74(9)*. pp. 1468-1474. Available: https://pubmed.ncbi.nlm.nih.gov/30358818/

[6] J. Murphy and B. Isaacs. (1982). The post-fall syndrome. A study of 36 elderly patients. *Gerontology*. [Online]. *28(4)*. pp. 265-270. Available: https://pubmed.ncbi.nlm.nih.gov/7117852/

[7] A. Shumway-Cook and M. H. Woollacott. *Motor Control: Translating Research into Clinical Practice.* Pennsylvania, Philadelphia: Lippincott Williams & Wilkins, 2007.

[8] J. Mehta, G. Czanner, S. Harding, D. Newsham, and J. Robinson. (2022, February). Visual risk factors for falls in older adults: a case-control study. *BMC Geriatr*. [Online]. *22(1)*. pp. 134. Available: https://pubmed.ncbi.nlm.nih.gov/35177024/

[9] S. R. Lord and J. C. T. Close. (2018 July). New horizons in falls prevention. *Age Ageing*. [Online]. *47(4)*. pp. 492-498. Available: https://pubmed.ncbi.nlm.nih.gov/29697780/

[10] E. Thomas, G. Battaglia, A. Patti, et al. (2019, July). Physical activity programs for balance and fall prevention in elderly: A systematic review. *Medicine (Baltimore)*. [online]. *98(27)*. pp. e16218. Available: https://pubmed.ncbi.nlm.nih.gov/31277132/

[11] H. Feng, C. Li, J. Liu, et al. (2019, June). Virtual reality rehabilitation versus conventional physical therapy for improving balance and gait in Parkinson's disease patients: A randomized controlled trial. *Med Sci Monit*. [Online]. *25*. pp. 4186-4192. Available: https://pubmed.ncbi.nlm.nih.gov/31165721/

[12] I. J. de Rooij, I. G. van de Port, and J. G. Meijer. (2016, December). Effect of virtual reality training on balance and gait ability in patients with stroke: Systematic review and meta-Analysis. *Phys Ther*. [Online]. 96(12). pp. 1905-1918. Available: https://pubmed.ncbi.nlm.nih.gov/27174255/

[13] T. In, K. Lee, and C. Song. (2016, October). Virtual reality reflection therapy improves balance and gait in patients with chronic stroke: randomized controlled trials. *Med Sci Monit*. [Online]. 22. pp. 4046-4053. Available: https://pubmed.ncbi.nlm.nih.gov/27791207/

[14] T. Prasertsakul, P. Kaimuk, W. Chinjenpradit, W. Limroongreungrat, and W. Charoensuk. (2018, September). The effect of virtual reality-based balance training on motor learning and postural control in healthy adults: a randomized preliminary study. *Biomed Eng Online*. [Online]. *17(1)*. pp. 124. Available: https://pubmed.ncbi.nlm.nih.gov/30227884/

[15] G. Duque, D. Boersma, G. Loza-Diaz, et al. (2013). Effects of balance training using a virtual-reality system in older fallers. *Clin Interv Aging.* [Online]. *8.* pp. 257-263. Available: https://pubmed.ncbi.nlm.nih.gov/23467506/

[16] R. Llorens, E. Noe, C. Colomer, and M. Alcaniz. (2015, March). Effectiveness, usability, and cost-benefit of a virtual reality-based telerehabilitation program for balance recovery after stroke: A randomized controlled trial. *Arch Phys Med Rehabil*. [Online]. *96(3)*. pp. 418-425 e2. Available: https://pubmed.ncbi.nlm.nih.gov/25448245/

[17] M. F. Levin, P. L. Weiss, and E. A. Keshner. (2015, March). Emergence of virtual reality as a tool for upper limb rehabilitation: incorporation of motor control and motor learning principles. *Phys Ther.* [Online]. *95(3).* pp. 415-425. Available: https://pubmed.ncbi.nlm.nih.gov/25212522/

[18] H. S. Patrice L. (Tamar) Weiss, Debbie Rand, Rachel Kizony. (2009). Video capture virtual reality: A decade of rehabilitation assessment and intervention. *Phys Ther Rev*. [Online]. *14(5)*. pp. 307-321. Available: https://www.tandfonline.com/doi/abs/10.1179/108331909X12488667117339

[19] P. N. Wilson, N. Foreman, and M. Tlauka. (1996, December). Transfer of spatial information from a virtual to a real environment in physically disabled children. *Disabil Rehabil.* [Online]. *18(12).* pp. 633-637. Available: https://pubmed.ncbi.nlm.nih.gov/9007423/

[20] H. Sveistrup. (2004, December). Motor rehabilitation using virtual reality. *J Neuroeng Rehabil*. [Online]. 1(1). pp. 10. Available: https://pubmed.ncbi.nlm.nih.gov/15679945/

[21] R. S. Renner, B. M. Velichkovsky, and J. R. Helmert. (2013). The perception of egocentric distances in virtual environments - A review. *ACM Computing Surveys*. [Online]. *46(2)*. pp. 1-40. Available: https://dl.acm.org/doi/10.1145/2543581.2543590

[22] R. J. Peterka. (2002). Sensorimotor integration in human postural control. *J Neurophysiol.* [Online]. *88(3)*. pp. 1097-1118. Available: https://pubmed.ncbi.nlm.nih.gov/12205132/#:~:text=It%20is%20generally%20accepted%20that,vestibular%2C%20and%20proprioceptive%20sensory%20systems.

[23] C. G. C. Horlings, M. G. Carpenter, U. M. Kung, F. Honegger, B. Wiederhold, and J. H. Allum. (2009, February). Influence of virtual reality on postural stability during movements of quiet stance. *Neurosci Lett.* [Online]. *451(3).* pp. 227-231. Available: https://pubmed.ncbi.nlm.nih.gov/19146921/

[24] R. Almajid, C. Tucker, E. Keshner, E. Vasudevan, and W. G. Wright. (2021, March). Effects of wearing a head-mounted display during a standard clinical test of dynamic balance. *Gait Posture.* [Online]. *85.* pp. 78-83. Available: https://pubmed.ncbi.nlm.nih.gov/33517040/

[25] M. Morel, B. Bideau, J. Lardy, and R. Kulpa. (2015, November). Advantages and limitations of virtual reality for balance assessment and rehabilitation. *Neurophysiol Clin.* [Online]. *45(4-5).* pp. 315-326. Available: https://pubmed.ncbi.nlm.nih.gov/26527045/

[26] N. Kato, T. Iuchi, K. Murabayashi, and T. Tanaka. (2023, July). Comparison of smoothness, movement speed and trajectory during reaching movements in real and virtual spaces using a head-mounted display. *Life (Basel).* [Online]. *13(8).* 1618. Available: https://pubmed.ncbi.nlm.nih.gov/37629476/

[27] K. Taneda, H. Mani, N. Kato, et al. (2021, May). Effects of simulated peripheral visual field loss on the static postural control in young healthy adults. *Gait Posture.* [Online]. *86.* pp. 233-239. Available: https://pubmed.ncbi.nlm.nih.gov/33774584/#:~:text=Peripheral%20visual%20field%20loss%20reduced,AP%20direction%20to%20maintain%20equilibrium.

[28] J. E. Cutting and P. M. Vishton, “Chapter 3 - Perceiving layout and knowing distances: The integration, relative potency, and contextual use of different information about depth (*Book style*)*," in *Perception of Space and Motion*, W. Epstein and S. Rogers, Eds. San Diego: Academic Press, 1995, pp. 69-117.
[29] E. B. Goldstein and L. Cacciamani, *Sensation and Perception* (11th Edition, *Book style*). Boston, MA: Cengage Learning, 2021.
[30] N. Kato, T. Tanaka, S. Sugihara, K. Shimizu, and N. Kudo. (2016, April). A study of the effect of visual depth information on upper limb movement by use of measurement of smoothness. *J Phys Ther Sci*. [Online]. *28(4)*. pp. 1134-1141. Available: https://pubmed.ncbi.nlm.nih.gov/27190441/
[31] T. E. Prieto, J. B. Myklebust, R. G. Hoffmann, E. G. Lovett, and B. M. Myklebust, “Measures of postural steadiness: differences between healthy young and elderly adults,” *IEEE Trans Biomed Eng*, vol. 43, no. 9, Sep. 1996, pp. 956-966.
[32] S. R. Lord and H. B. Menz. (2000, November to December). Visual contributions to postural stability in older adults. *Gerontology*. [Online]. *46(6)*. pp. 306-310. Available: https://pubmed.ncbi.nlm.nih.gov/11044784/#:~:text=Conclusion%3A%20The%20study%20findings%20confirm,and%20falls%20in%20older%20people.
[33] A. M. Bronstein and D. Buckwell. (1997, February). Automatic control of postural sway by visual motion parallax. *Exp Brain Res*. [Online]. *113(2).* pp. 243-248. Available: https://pubmed.ncbi.nlm.nih.gov/9063710/
[34] M. G. Carpenter, J. S. Frank, D. A. Winter, and G. W. Peysar. (2001, February). Sampling duration effects on centre of pressure summary measures. *Gait Posture*. [Online]. *13(1)*. pp. 35-40. Available: https://pubmed.ncbi.nlm.nih.gov/11166552/

Norio Kato is an Associated Professor at Hokkaido University of Science. He received his PhD from Hokkaido University, in 2016. His research of interest includes Virtual Reality, IoT, Kinesiology, Rehabilitation Science and Assistive Engineering.

Toshiaki Tanaka is a Professor at The University of Tokyo and Hokkaido University of Science. He received his PhD from Hokkaido University, in 1998. His research of interest includes Kinesiology, Rehabilitation Science, Ergonomics, and Assistive Engineering. He is a Board of Director, The Japanese Society for Wellbeing Science and Assistive Technology. He is author of a book, Science of Balance Training for Preventing a Falling (2013) and a coauthor of a book, Eye Movement Input Device Designed to Help Maintain Amyotrophic Lateral Sclerosis (ALS) Patients (2012). He has published over 170 research papers in his research of interest.