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ORIGINAL

Analysis of Stability on Single-leg Standing by Wearing a Head Mounted Display

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Objective: The purpose of this study was to investigate the effects of three visual conditions (eyes opened, eyes closed, and wearing of a head mounted display [HMD]) on single-leg standing through kinematics and kinetic analysis.

Method: Twelve college students (age: 24.5±2.6 years, height: 175.0±6.4 cm, weight: 69.2±5.1 kg) participated in this study. The study method adopted three-dimensional analysis with six cameras and ground reaction force measurement with one force plate. The analysis variables were coefficient of variation (CV) of the center of body mass, head movement, ground reaction force, and center of pressure, which were analyzed using one-way analysis of variance with repeated measures according to visual conditions.

Results: In most cases, the results of this study showed that the CV was significantly higher in the order of HMD wearing, eyes closed, and eyes opened conditions.

Conclusion: Our results indicated that body sway was the largest in the HMD wearing condition, and the risk of falling was high owing to the low stability.

Keywords: Virtual reality, Head mounted display, Balance, Stability

INTRODUCTION

Virtual reality (VR) is an interactive simulation that allows people to experience real-life situations through computer hardware and software (Chan et al., 2010; Rizzo & Buckwalter, 1997). Interactive simulation enables the brain to perceive a simulated situation as a reality through the stimulation of multiple sensory systems, which can be effectively controlled by visual and auditory feedback (Bruin et al., 2010; Deutsch et al., 2004; Flynn et al., 2007). This VR effectively controls movements with various and immediate feedbacks and induces interests and amusements, leading to active performance of the task (Chan et al., 2010; Kizony et al., 2004; Rizzo & Buckwalter, 1997). In recent years, lightweight helmets and head mounted displays (HMDs) have improved immersion in three-dimensional (3D) environments through 360° viewing angles with low-cost VR systems (Robert et al., 2016; Schubert et al., 2001).

However, there are emerging concerns about the use of VR. According to previous studies on the potential impact of VR technology (Kennedy & Lilienthal, 1995; Kennedy & Stanney, 1996; Kolasinski et al., 1994; Kolasinski, 1996), the subjects raised the issue of posture safety when returning to daily life from a newly simulated environment and reported experiencing cybersickness (Cobb & Nichols, 1998).

Cybersickness refers to motion sickness that occurs in VR and is also known as simulator sickness. It is generally known to be caused by sensory collision or nervous mismatch. It also includes mismatches between actual behavior and information in the brain (Balaban, 1999). The Simulator Sickness Questionnaire, developed by Kennedy et al. (1993) as a measurement tool for cybersickness, classifies cybernetic symptoms into three categories: disgust, ocular motility disorientation, and disorientation.

The ability to control posture to maintain balance is essential in daily life (Cohen et al., 1993), which degenerates as aging progresses (Daubney & Culham, 1999). This posture control is a difficult task that requires integration of various sensory systems such as vision, vestibule, and proprioceptive senses. In the posture control systems, the symptom of balance disorder increases visual dependency, which may be due to the compensatory action of the various sensory systems (Tossavainen et al., 2003). For successful stability, movement of the feet should maintain the balance on a small basal plane to maintain the center of body mass (Nashner, 1994), and perturbation of this balance state continuously occurs during both standing and moving (Winter, 1995). For this reason, it is necessary to investigate the loss in sense of direction, that is, the posture stability under the VR condition, when using the VR.

In a preceding study, Kim et al. (2015) evaluated the effects of proprioceptive sensory disturbance induction and HMD wearing on the area of the pressure center shift and velocity in standing position.

Yoo et al. (2011) investigated the effect of HMD in game consoles on the improvement of balance and visual perceptive ability of patients with hemiplegia due to stroke. Woo et al. (2004) revealed the correlation between the ability of static posture and muscle activity through HMD, and Kim et al. (1996) conducted a study on balance control through visual stimulation through VR, by using HMD in Korea for the first time.

Kim et al. (2017) assessed the stability of VR gait training with HMD for elderly patients with Parkinson's disease, and Robert et al. (2016) evaluated the effects of HMD wearing in a virtual setting created from images of reality on static and dynamic balance. Mustonen et al. (2013) used monocular HMDs to investigate the effects of gait on visual tasks; Berard et al. (2012) analyzed the abilities of elderly and young subjects in processing sensory information during walking depending on speed and visual perturbation in the HMD wearing state; and Lott et al. (2003) validated the effects of uses of flat-screen and HMD VR. Yi et al. (2014) revealed the relationship between upright posture mechanics and physical fitness in the elderly; Oh et al. (2011) analyzed the effects of exercise fatigue and interception of visual information on upright posture; and Lee (2005) conducted a study on postural control mechanisms. VR has been applied to research in various ways, such as sensory receptive ability and stability analysis, depending on rehabilitation and aging, targeting patients and persons with disabilities. Therefore, it is necessary to quantitatively evaluate the effect of cybersickness on body movements through the wearing of HMD, which is an immersive VR equipment, as well as to find ways to reduce cybersickness.

Although research related to VR has been receiving more attention lately, more studies need to be conducted. In particular, research in the field of physical and kinetic mechanics has been rarely performed. Therefore, the purpose of this study was to investigate the effect of wearing HMD, a VR equipment that has been actively commercialized, on body balance during a standing on one leg.

METHOD

1. Subjects

In this study, 12 male college students (age: 24.5±2.6 years, height: 175.0±6.4 cm, weight: 69.2±5.1 kg) participated. They were given explanation about the study before beginning the experiment, showed the intention to participate, and then submitted a consent form.

2. Equipment and procedures

Six kinematic infrared cameras (Motionmaster 100) and a 3D motion analysis system (Kwon 3D XP; Visol, Korea) were used for kinematic analysis of movements of the center of body mass and the head, and the ground reaction force (GRF) and center of pressure (COP) were measured by using a GRF platform (AMTI OR6-7-2K, USA) for kinematic analysis. To set up a motion analysis system, a control point (2 m × 2 m × 1 m) was installed in the experimental space to set the global coordinate system, in which the lateral direction was set as the X-axis, the anteroposterior direction as the Y-axis, and the vertical direction as the Z-axis with respect to the front face of the subject (Figure 1-B). To measure the center of gravity (CG), 18 ball markers were attached to each part of the subject's body (sacrum, superior anterior iliac spine, left and right knees, right and left ankles, left and right heels, left and right toes, left and right shoulders, left and right wrists, and the upper center of the device when the HMD was worn), followed by digitizing. The coordinates of the center of the human segment were obtained using the body segment parameters of Plagenhoef et al. (1983), and the 2D coordinate values obtained from the camera were converted to 3D coordinates by using the direct linear transformation method (Abdel-Aziz & Karara, 1971). To solve the error occurring in digitizing and the error of skin markers, all 3D coordinate values were filter processed. Noise generated during data analysis was smoothed using digital filtering, and the cutoff frequency of the low-pass filter was set to 10 Hz. The GRF for sampling was set at 1,000 Hz, and the collected data were analyzed using an analysis program (KwonGRF 2.0; Visol, Korea). Noise was removed by applying a low-pass filter of 20 Hz. In addition, the data were standardized according to the weight of each subject for processing.

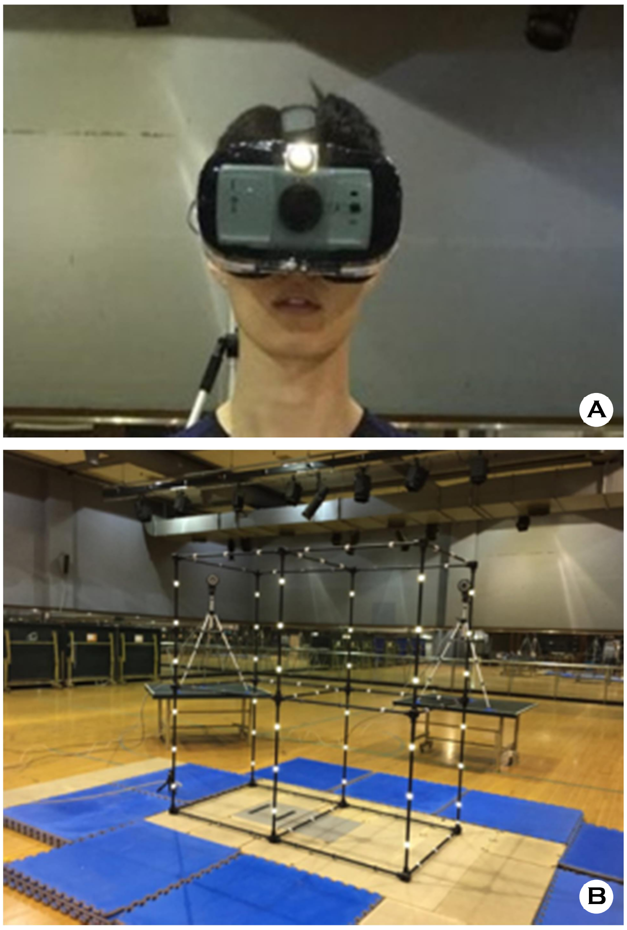

Figure 1. Experimental equipment: (A) head mounted display set; (B) experimental setup

The subjects stood on one leg with the eyes opened (EO), with the eyes closed (EC), and while wearing an HMD (Coms-WH0126); these were repeated three times per subject (Figure 1-A). We used an eye

Table 1. Results of CV of CG and head (unit: %CV)

Condition \ Axis	CG X	CG Y	CG Z	Head X	Head Y	Head Z
EO	0.74±0.76	3.02±3.01	0.12±0.21	2.66±2.85	1.68±1.81	0.17±0.26
EC	1.61±1.54	8.22±9.41	0.37±0.29	10.75±11.40	3.02±1.39	0.29±0.16
HMD	7.91±7.58	13.02±10.63	0.55±0.50	45.01±63.23	4.13±1.93	1.06±0.84
F-value	**25.001*****	**11.401*****	**29.334*****	**14.700*****	**11.740*****	**18.147*****
Bonferroni	EO<EC<HMD	EO<EC, HMD	EO<EC, HMD	EO<EC<HMD	EO<EC<HMD	EO<EC<HMD

Note. Significant at ***$p<0.001$.
EO: eyes opened, EC: eyes closed, HMD: head mounted display

patch to block the vision; the smartphone worn on the HMD was Samsung Galaxy S6; and the images displayed on the smartphone when using the HMD were those recorded in the laboratory to match with other experimental conditions. The knee joint was measured by flexing the left knee joint to 90° while holding both hands on the waist for 15 s. If the subject lost balance or fell, the motion was repeated.

3. Data processing

To remove various variables such as initial body sway at the time of standing on one leg, data were analyzed from 5 s after the start of the experiment during a total of 15 s. For all subjects, the mean and standard deviation of the data corresponding to the last 10 s were obtained, from which the coefficient of variation (CV) was calculated, and the calculated variabilities were averaged, which were used for comparison depending on the visual condition.

$$\%CV = \frac{Standard\ deviation}{Mean} \times 100.$$

4. Statistical analysis

Statistical analysis was performed with SPSS 21.0 (IBM, USA). From the calculated mean and standard deviation, variability was obtained. One-way analysis of variance with repeated measures was used to analyze the difference of the center of body mass, head movement, GRF, and pressure center variability depending on three visual conditions (EO, EC, and HMD wearing), whereas the Bonferroni method was used for post-hoc analysis. The significance level of all statistics was set at $p<0.05$.

RESULTS

1. Results of CV of CG and head

The body-centered variability analysis found differences in the X-axis depending on the condition [$F=25.001$, $p=0.000$], and post-hoc analysis

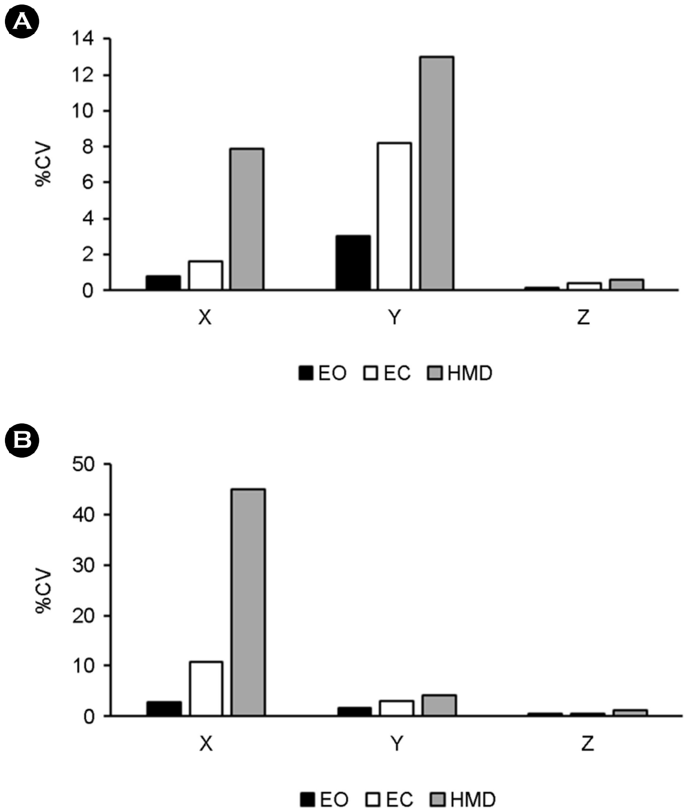

Figure 2. Results of coefficient of variation (CV) of the center of gravity (A) and that of CV of the head (B) for each group (EO: eyes opened, EC: eyes closed, HMD: head mounted display)

also found higher variability in order of HMD, EC, and EO. The Y-axis showed a difference depending on the condition [$F=11.401$, $p=0.000$], and the results of the post-hoc analysis showed that HMD showed the greatest variability, followed by EC and EO in order. The Z-axis showed a difference depending on the condition [$F=29.334$, $p=0.000$], and HMD and EC showed greater variability than EO in post-hoc analysis (Table 1, Figure 2).

Analysis of variability of the head found differences depending on the condition on the X-axis [$F=14.700$, $p=0.000$], and the results of the post-hoc analysis showed that HMD had the greatest variability, followed by EC and EO in order. The Y-axis showed a difference depending on the condition [F=11.740, p=0.000], and the results of the post-hoc analysis showed that HMD had the greatest variability, followed by EC and EO in order. The Z-axis had a difference depending on the condition [F=18.147, p=0.000], and the results of the post-hoc analysis showed that HMD had the greatest variability, followed by EC and EO in order (Table 1, Figure 2).

2. Results of CV of GRF

In the results of the analysis of variability in the GRF, Fx showed a difference depending on the condition [F=45.823, p=0.000], and the post-hoc analysis found that HMD had the greatest variability, followed by EC and EO in order. Fy was different depending on the condition [F=17.405, p=0.000], and HMD and EC showed higher variability than EO. Fz varied depending on the condition [F=72.562, p=0.000], and the results of the post-test showed that HMD had the greatest variability, followed by EC and EO in order (Table 2, Figure 3).

Table 2. Results of coefficient of variation (CV) of ground reaction force (unit: %CV)

Condition \ Force	Fx	Fy	Fz
EO	107.66± 163.58	-69.50± 517.71	0.60± 0.12
EC	268.28± 93.54	212.05± 1492.11	1.19± 0.40
HMD	664.67± 467.15	1356.58± 1366.19	4.02± 4.20
F-value	**45.823*****	**17.405*****	**72.562*****
Bonferroni	EO<EC<HMD	EO, EC<HMD	EO<EC<HMD

Note. Significant at ***p<0.001.
EO: eyes opened, EC: eyes closed, HMD: head mounted display

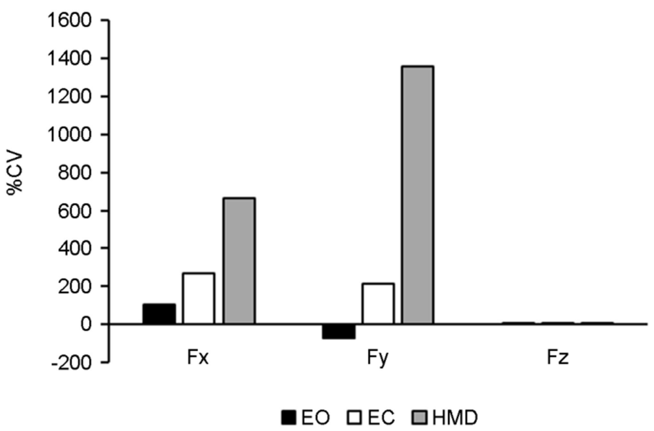

Figure 3. Results of coefficient of variation (CV) of ground reaction force (EO: eyes opened, EC: eyes close, HMD: head mounted display)

3. Results of CV of COP

The analysis of variability in the pressure center found a difference in the lateral direction [F=27.617, p=0.000]. After the post-hoc analysis, the variability was higher in order of HMD, EC, and EO. There was also a difference in the anteroposterior direction [F=48.302, p=0.000], and post-hoc analysis found a higher variability following the order of HMD, EC, and EO (Table 3, Figure 4).

Table 3. Results of coefficient of variation (CV) of center of pressure (unit: %CV)

Condition \ Direction	M-L	A-P
EO	1.87±0.42	2.90±0.80
EC	3.40±1.52	5.56±1.53
HMD	6.13±5.35	8.15±4.04
F-value	**27.617*****	**48.302*****
Bonferroni	EO<EC<HMD	EO<EC<HMD

Note. Significant at ***p<0.001.
M-L: medio-lateral, A-P: anteroposterior, EO: eyes opened, EC: eyes closed, HMD: head mounted display

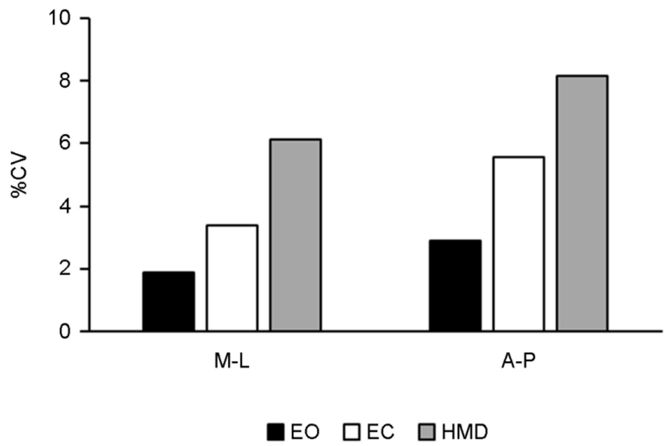

Figure 4. Results of coefficient of variation (CV) of center of pressure (EO: eyes opened, EC: eyes closed, HMD: head mounted display)

DISCUSSION

In this study, 12 male college students were analyzed for stability in a standing posture on one leg in the EO, EC, or VR HMD wearing states.

According to the visual condition, the variability of the center of body was higher in the order of HMD wearing, EC, and EO states in both X- and Y-axes. In the Z-axis, the HMD wearing and EC states had a higher variability than the EO state. In the variability of the head, the X-, Y-, and Z-axes all showed greater variability in the order of HMD wearing, EC, and EO states. As for the GRF, there was a significant variability in the order of HMD wearing, EC, and EO states in Fx and Fz. In Fy, the HMD wearing state had a significantly higher variability than the EC or EO state, and the pressure center showed a greater variability in the order of HMD wearing, EC, and EO states in both the lateral and anteroposterior directions.

In a preceding study, Huurnink et al. (2013) reported that the velocity of the COP decreased in the EO state rather than in the EC state. Hazime et al. (2012) used visual disturbance and inherent receptive sensory disturbance during standing with one leg and standing on both legs, and reported that inherent receptive sensory disturbance affected the balance of the legs; however, the role of visual cognition was more important than inherent receptive sensation when standing on one leg. Park et al. (2011) measured balance among adults with or without visual impairment, by which they reported that as for the visual cortex, the shift area of the COP and mean velocity were 1.2~1.8 times higher, and the shift rate of the COP in the EC state increased compared with that in the EO state.

Woo et al. (2014) compared three visual conditions (EO, EC, and virtual setting) in a stable standing position with the legs spread 20 cm apart and an unstable standing position with legs pinched together. All three visual conditions had a difference in balancing ability owing to differences in baseline between stable and unstable standing positions.

Kim et al. (2015) induced vestibular sensation disturbance by wearing HMD, and then analyzed the effect on COP. Among six conditions (EO, EC, EO with vibrator attached, EO with HMD wearing, vibrator + HMD wearing, and EC with vibrator attached), the EC, HMD wearing, and vibrator + HMD wearing states were reported to be the most unstable, with the HMD wearing state being the least stable. Horlings et al. (2009) reported that adults who were wearing VR glasses showed more physical sway, and the physical fluctuations were similar to those in the EC state.

However, Robert et al. (2016) argued against the study by Horlings et al. (2009), because it was difficult to directly compare the two settings owing to the absence of a similar visual representation and expression of a smaller visual field than the VR HMD. Instead, Robert et al. (2016) compared COP based on the difference between real and virtual settings. They found no difference in the lateral direction, anteroposterior direction, and total COP in both the EO and EC states, and also no difference in the anteroposterior direction between the EO and EC states in the real setting, whereas there was a difference only in the total COP. In addition, they reported that the virtual setting had no difference in the frontal, lateral, and total COP between the EO and EC states, and similar results have been reported in a study by Chiarovano et al. (2015). In the present study, the visual representation of the VR was constructed in the same manner as in the EO state; however, our results were more similar to those of Horlings et al. (2009) than to those of Robert et al. (2016) and Chiarovano et al. (2015).

Among the overall results of this study, only the vertical variability in the center of body mass showed no difference between the HMD wearing and EC states, and the HMD wearing state had higher variabilities in most results; thus, it seems that the virtual setting greatly induced body sway. Particularly, high variability was found in the anteroposterior direction for the center of body mass, in the lateral direction for the head, in the lateral force and the longitudinal force for the GRF, and in the anteroposterior direction for the pressure center. As movement of the sagittal plane can be largely observed in the upright posture owing to the structure of the lower limbs, it was concluded that there was a large variability in the forward and backward movements and the force.

Woo and Sul (2016) reported that as the sagittal plane had a higher range of joint motion in the body than the coronal plane, the variability increased, which was similar to the results of the present study. When wearing HMD in this study, high body sway was found, which was similar to a preceding study showing that cybersickness was caused by mismatch between the orientation of sight and head movements, and increased eye movement following the screen, leading to sensory collisions, nervous mismatches, and mismatches between actual behavior and brain information. Hence, it is believed that this caused difficulties in maintaining balance. Therefore, when using HMD, safety equipment must be worn while complying with safety regulations, and it is necessary either to match the orientation of sight and the head movement or to develop HMD equipment for this goal. To this end, a VR technology is currently being developed to reduce cybersickness. If these problems are solved, the issue of balance control will naturally be resolved. During normal postural control, information from visual, auditory, tactile, vestibular, and sensory receptive senses are added to the vestibular nuclei to control posture after information exchange with the cerebellum (Lundy-Ekman, 2013); thus, it is considered suitable for rehabilitation exercises and training programs using the adaptation effect of information exchange and proprioceptive sense through body sway with VR.

CONCLUSION

The purpose of this study was to investigate the effects of three visual conditions (EO, EC, and HMD wearing) on the standing posture through examining the center of body mass, head movements, GRF, and pressure center variability. Kinematic and kinematical data were collected in the given visual conditions and analyzed using 3D motion analysis and a GRF platform for 12 college students. The conclusions are as follows.

First, the body-centered variability was greater in the order of HMD wearing, EC, and EO states in all X-, Y-, and Z-axes.

Second, the variability of head movement was higher in the order of HMD wearing, EC, and EO states in all X-, Y-, and Z-axes.

Third, Fx and Fz for variability in GRF were higher in the order of HMD wearing, EC, and EO states. Fy had greater variability in the HMD wearing state than in the EO and EC states.

Fourth, the variability of the pressure center was higher in the order of HMD wearing in both horizontal and anteroposterior directions, EC, and EO states.

This study showed that the HMD wearing state had the largest body sway, which suggests that the risk of falling should be high owing to a considerably low stability. To exclude directional factors such as cybersickness in wearing HMD, it seems necessary to develop appropriate equipment and use safety equipment. Through this study, we examined the influencing factors on the stability of the VR HMD, which is one of four industrial items. In the future, it will be necessary to analyze various images through HMD and to study visual movement and head movement, which are expected to be activated further.

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