



## Comparison of Gait Parameters during Forward Walking under Different Visual Conditions Using Inertial Motion Sensors

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**Purpose:** Gait evaluation in patients with dizziness is essential during both initial evaluation and vestibular rehabilitation. Inertial measurement unit (IMU)-based gait analysis systems are clinically applicable in patients with dizziness. Since dizzy patients can utilize visual inputs to compensate for vestibular deficits, it is more difficult for them to walk with their eyes closed (EC). In this study, we compared gait characteristics during forward walking with both eyes open (EO) and EC between healthy subjects and dizzy patients.

**Materials and Methods:** Forty-nine healthy controls (mean age 37.18±10.71 years) and 23 patients with dizziness (mean age 49.25±15.16 years) were subjected to vestibular and gait analyses. Medical histories, physical examinations, and vestibular function tests ruled out possible vestibular deficits in the controls. Subjects were instructed to walk at a comfortable pace for 10 m under two conditions (EO or EC). Spatiotemporal parameters, kinematics, and simulated kinetics of each gait recording were recorded using a shoe-type IMU system and analyzed.

**Results:** Although gait speeds were slower, stride lengths were smaller, and double support times were increased under the EC, compared to the EO condition, in both healthy subjects and dizzy patients, the difference was more prominent in dizzy patients. Phase coordination index values did not differ significantly in either group. Gait asymmetry (GA) increased significantly under the EC condition, compared to the EO condition, in dizzy patients.

**Conclusion:** GA during forward walking was greater in dizzy patients under an EC condition than under an EO condition.

**Key Words:** Dizziness, gait analysis, postural balance, inertial measurement unit

### INTRODUCTION

The ability to maintain balance under both static and dynam-

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ic conditions is crucial to ensure autonomy and safety in daily activities. Evaluation of gait, particularly gait speed, has been used to measure frailty and fall risk in older populations.<sup>1,2</sup> Balance control and gait stabilization require integration of the visual, vestibular, and proprioceptive systems. Vestibular disorders have been shown to be associated with gait abnormalities: patients with vestibular dysfunction exhibit a slower gait speed, more gait variability, and poorer coordination than healthy individuals.<sup>3-7</sup>

Gait evaluation of patients with vestibular dysfunction is essential during both initial assessment and treatment. Clinically, it is crucial to identify gait abnormalities during the initial evaluation, because these greatly affect the patient's ability to perform activities of daily living. Also, the obtained information is helpful for assessing the risk of falls and allows clinicians to provide appropriate guidance to prevent further injury. Vestib-

ular rehabilitation involves an exercise-based program that encourages vestibular adaptation and substitution to improve function and reduce dizziness during daily activities.<sup>7</sup> Gait analysis provides the information necessary to guide exercise selection and monitor progression during a vestibular rehabilitation program. Recently, inertial-sensor technology has been used for balance and gait analysis.<sup>9-12</sup> Compared to motion-capture systems, which require a large working space and expensive equipment, 3D inertial measurement units (IMUs) are small and light. As repeated measurements may be needed in patients with dizziness, wearable IMUs with a few attachments are clinically useful. Also, comprehensive measurements of spatiotemporal gait parameters can be obtained when the gait speed, surface (floor or treadmill), or direction (forward or backward) is varied.<sup>9,10,13,14</sup> When the vestibular sensory input is compromised, sensory reweighting of visual inputs serves as a compensatory strategy; this is particularly evident in patients with bilateral vestibulopathy who find it difficult to walk in the dark.

In this study, to provide baseline data for further studies, we compared gait characteristics during forward walking with the eyes open (EO) and the eyes closed (EC) between healthy subjects and dizzy patients. We hypothesized that even if subtle effects of vestibular dysfunction were masked during gait with the EO, they would be apparent when walking with the EC.

## MATERIALS AND METHODS

### Study population

This prospective study was conducted at a university-affiliated, tertiary referral hospital. Forty-nine healthy subjects participated voluntarily. They reported no history of neuromuscular or neurologic disorders known to cause gait disturbance, such as Parkinson's disease, and no history of otologic disease or dizziness symptoms during the previous year. In addition, 23 patients with dizziness were recruited from the outpatient Otorhinolaryngology Clinic of Gangnam Severance Hospital. Clinical diagnoses of the patients based on a thorough review of medical histories and audiovestibular tests included unilateral vestibular hypofunction (UVH), benign paroxysmal positional vertigo (BPPV), vestibular schwannoma (VS), and non-specific dizziness. UVH was defined as acute onset of vertigo, with confirmed UVH (canal paresis >25% in the caloric test). Patients were diagnosed with BPPV when they experienced recurrent attacks of positional vertigo, with each attack lasting <1 min, and had evidence of position-specific nystagmus on videonystagmography. Patients with VS (confirmed on the basis of magnetic resonance imaging scans) and UVH (canal paresis >25% or decreased gain of <0.8 in the video head impulse test) were included. Non-specific dizziness was diagnosed when central or peripheral vestibular disorders were excluded on the basis of brain imaging and vestibular function tests in patients

with chronic dizziness lasting for >3 months. The clinical characteristics of the study population are listed in Table 1.

We performed a priori power analysis to determine the minimum sufficient sample size for an effect size of 0.8, power of 0.8, and significance value ( $\alpha$ ) of 0.05 for healthy subjects and dizzy patients (at a ratio of 2:1). Based on this analysis, the study required a minimum of 39 healthy subjects and 19 dizzy patients. Assuming a drop-out rate of 20%, a minimum of 49 healthy subjects and 23 dizzy patients were required.

The Institutional Review Board of Gangnam Severance Hospital approved the study protocol (approval number: 3-2018-0182). Written informed consent was obtained from all subjects. All study procedures were performed in accordance with all relevant tenets of the Declaration of Helsinki.

### Equipment and data collection

Shoe-type, IMU-sensor-based gait analysis systems (DynaStab; JEIOS, Seoul, South Korea) used in this study included a shoe-type data logger (Smart Balance SB-1; JEIOS) and a data acquisition system. The IMU sensor (IMU-3000; InvenSense, San Jose, CA, USA) of the data logger measured tri-axial acceleration (up to  $\pm 6$  g) and tri-axial angular velocity (up to  $\pm 500^\circ/\text{s}$ ) along three orthogonal axes.<sup>13-15</sup> IMU sensors were installed in the outsoles of both shoes, and the data were transmitted wirelessly to a data acquisition system via Bluetooth. Shoes that fitted the subjects well were chosen: available sizes ranged from 225 mm to 280 mm. A local coordinate system (anteroposterior, mediolateral, and vertical directions) was established for the IMU sensors. The subjects were asked to walk along a 10-m walkway at a comfortable pace, first with the EO and then with the EC. A tester walked next to each subject to ensure safety. The subjects were encouraged to take a short break between the two walks if needed.

### Data analysis

All data were obtained using the IMU-sensor-based gait analysis system.<sup>13-15</sup> The local minimum and maximum values of linear acceleration and angular velocity of pitching were used to determine the temporal features of the gait. Spatial and temporal gait parameters were calculated for each stride made by each foot based on the heel strike; the means and SDs of gait parameters were subjected to statistical analysis. The first and final two steps (acceleration and deceleration phases, respectively) from each walking trial were excluded from the analysis. Bilateral gait coordination was evaluated by calculating phase coordination index (PCI) and gait asymmetry (GA) by the raw step and stride time data using R software (R Development Core Team, 2014).<sup>16</sup> PCI quantifies the degree of consistency and the accuracy of left-right stepping using a vector series of the left-right stepping phase ( $\phi$ ; ideally =  $180^\circ$ ). The stride duration of one foot was defined as the time taken for a gait cycle or  $360^\circ$ , and the relative timing of contralateral heel-strikes was defined as the phase  $\phi$ , which would ideally be  $180^\circ$

for every step. The sum of the coefficient of variation of  $\phi$  and the mean absolute difference between  $\phi$  and  $180^\circ$  were defined as the PCI.<sup>17</sup> A lower PCI value indicates higher consistency and accuracy in terms of bilateral gait coordination, while a higher value denotes a lack of consistency and accuracy.<sup>17,18</sup> GA was calculated as a logarithm of the time spent in each step by comparing the swing times of one leg with respect to the other leg.<sup>8,19</sup>  $GA=100 \times |\ln(SSWT/LSWT)|$ , where SSWT and LSWT represent the mean values of the swing times for the legs with the short and long mean swing times, respectively. To evaluate the difference between the EC and EO conditions, we calculated the “intrasubject differences” in the gait parameters between the EO and EC conditions for each subject.

In this study, we aimed to measure the increased difficulty of gait control experienced by the participants while walking in the EC condition, compared to the EO condition. Because the dizzy patients were presumed to have greater gait instability than normal subjects, even in the EO condition, it would not have been appropriate to compare the two subject groups directly. Thus, we compared parameters between each subject. To evaluate the differences between the EC and EO conditions, we calculated “intrasubject differences” in gait parameters between the EO and EC conditions for each subject.

**Statistical analysis**

All statistical analyses were performed using SAS software (ver. 9.3; SAS Institute Inc., Cary, NC, USA). The Shapiro-Wilk test and Kolmogorov-Smirnov tests were used to test for data distribution. The paired t-test was used to compare gait parameters between the EO and EC conditions. When data were not normally distributed, nonparametric tests were used for comparison. The chi-square test was used to compare nominal variables, and the Mann-Whitney U-test was used for continuous variables. The Wilcoxon signed-rank test was used to compare PCI and GA variables between the EO and EC conditions within each subject group. Data are presented as means±SD, and  $p < 0.05$  was considered to reflect statistical significance.

**RESULTS**

The clinical characteristics of the healthy subjects and dizzy patients are listed in Table 1. The patients were older ( $49.25 \pm 15.16$  years) than the healthy subjects ( $37.18 \pm 10.71$  years). There were no significant differences in sex, height, weight, body mass index, and foot size between the two groups. Spatiotemporal gait parameters were compared between EO and EC conditions in healthy subjects (Table 2). All gait parameters showed significant intrasubject differences between the EO and EC conditions. When the eyes were closed, healthy subjects tended to walk more slowly with shorter stride lengths; moreover, the duration of double support was increased, indicating that the subjects walked more carefully. Additionally, intrasubject differences between the EO and EC conditions were significantly different for all parameters. The dizzy patients walked more slowly in the EC condition than under the EO condition. There were significant difference between the EO and EC conditions in stride length and single support duration, and double support duration (Table 3).

Next, the gait coordination parameters (PCI and GA) were compared between the EO and EC conditions (Table 4). Overall, PCI was significantly higher for the EC condition, compared to the EO condition, in both healthy subjects and dizzy patients. However, the intrasubject differences in PCI between the EO and EC conditions did not differ significantly between the healthy subjects and dizzy patients ( $p=0.0546$ ). The healthy subjects showed no significant difference in GA between the EO and EC conditions. However, in dizzy patients, GA increased significantly under the EC condition, compared to under the EO. The intrasubject difference in GA (EC compared to EO condition) between healthy subjects and dizzy patients was statistically significant ( $p=0.0037$ ), implying that the intrasubject change in GA was significantly greater in dizzy patients than in healthy subjects. These findings imply that maintaining gait symmetry under the EC condition is more challenging for dizzy patients than for healthy subjects.

**Table 1.** Clinical Characteristics of the Study Population

Variables	Total (n=72)	Healthy controls (n=49)	Dizzy patients (n=23)
	n (%) or median (q1-q3), (min-max)	n (%) or median (q1-q3), (min-max)	n (%) or median (q1-q3), (min-max)
Sex			
Male	27 (37.50)	15 (30.61)	12 (52.17)
Female	45 (62.50)	34 (69.39)	11 (47.83)
Age (year)	40 (28.5–51.5), (18–77)	33(27–46), (23–58)	52 (40–58), (18–77)
Height (cm)	164 (159–170), (150–183)	163(159–168), (150–183)	167 (160–171), (154–176)
Weight (kg)	60 (53–73), (40–110)	60 (51–73), (44–110)	64 (55–70), (40–84)
BMI (kg/m <sup>2</sup> )	22.74 (20.32–25.27), (14.26–32.85)	22.22 (19.95–25.86), (17.75–32.85)	22.83 (21.78–24.97), (14.26–28.39)
Foot size (mm)	240 (235–257.5), (225–285)	240 (235–255), (225–285)	250 (240–265), (230–275)
Diagnosis		Healthy (n=49)	UVH (n=8), BPPV (n=2), VS (n=10), Non-specific dizziness (n=3)

BMI, body mass index; UVH, unilateral vestibular hypofunction; BPPV, benign paroxysmal positional vertigo; VS, vestibular schwannoma.

**Table 2.** Spatiotemporal Parameters in Healthy Subjects during Forward Walking Under the EO and EC Conditions (n=49)

	EO Median (q1-q3), (min-max)	EC Median (q1-q3), (min-max)	Difference (EO-EC) Median (q1-q3), (min-max)	p value
Gait speed (m/s)	1.667 (1.417–1.667), (1.111–2.000)	1.250 (1.111–1.417), (0.667–2.500)	0.306 (0.139–0.556), (0.500–1.000)	<0.0001*
Cadence (steps/min)	119.000 (112.000–125.000), (99.000–136.000)	114.000 (107.000–121.000), (78.000–133.000)	4.000 (1.000–9.000), (-5.000–44.000)	<0.0001*
Stride length (m)	1.638 (1.403–1.840), (1.083–2.113)	1.365 (1.243–1.553), (0.920–2.517)	0.226 (0.064–0.462), (-0.520–0.831)	<0.0001*
Single support (%cycle)	41.434 (40.500–42.316), (38.352–43.729)	40.441 (39.550–41.720), (32.081–43.402)	0.770 (0.177–1.361), (-0.946–8.222)	<0.0001*
Double support (%cycle)	17.116 (15.355–19.099), (12.542–23.260)	19.083 (16.539–20.916), (13.140–35.719)	-1.509 (-2.753–0.418), (-16.325–2.182)	<0.0001*
Time of toe off (%cycle)	58.703 (57.724–59.674), (56.271–61.551)	59.588 (58.205–60.493), (55.403–67.697)	-0.926 (-1.473–0.116), (-8.000–1.928)	<0.0001*

EO, eyes open; EC, eyes closed.

\*Significant difference between the EO and EC conditions ( $p < 0.05$ ).**Table 3.** Spatiotemporal Parameters in Dizzy Patients During Forward Walking Under the EO and EC Conditions (n=23)

	EO Median (q1-q3), (min-max)	EC Median (q1-q3), (min-max)	Difference (EO-EC) Median (q1-q3), (min-max)	p value
Gait speed (m/s)	1.142 (1.111–1.389), (0.778–1.667)	1.000 (0.833–1.250), (0.361–1.667)	1.667 (1.111–0.4167), (0.250–0.750)	0.0002*
Cadence (steps/min)	112.000 (109.000–122.000), (82.000–132.000)	112.000 (106.000–116.000), (100.000–130.000)	1.000 (-4.000–7.000), (-24.000–18.000)	0.3747
Stride length (m)	1.410 (1.228–1.548), (1.055–1.721)	1.143 (0.982–1.309), (0.403–1.704)	0.184 (0.093–0.412), (-0.220–0.742)	<0.0001*
Single support (%cycle)	40.322 (39.431–41.533), (36.804–43.026)	40.104 (38.040–41.310), (36.991–52.633)	0.461 (-0.361–1.772), (-15.611–3.612)	0.0418*
Double support (%cycle)	19.451 (16.934–21.248), (13.947–26.440)	19.804 (17.172–23.590), (-5.768–25.857)	-0.781 (-3.375–0.725), (-7.058–31.739)	0.0453*
Time of toe off (%cycle)	59.910 (58.467–60.823), (56.974–63.316)	59.898 (58.524–61.733), (43.287–62.684)	-0.316 (-1.261–0.639), (-2.920–19.722)	0.2317

EO, eyes open; EC, eyes closed.

\*Significant difference between EO and EC conditions ( $p < 0.05$ ).**Table 4.** Gait Coordination Parameters during Forward Walking in Healthy Subjects (n=49) and Dizzy Patients (n=23) Under the EO and EC Conditions

Variables	Group	EO	EC	p value (EO vs. EC)	Difference	p value (between groups)
PCI	Healthy subjects	3.78±2.18	12.57±33.06	0.0001*	-8.80±33.29	0.0546
	Dizzy patients	5.91±4.30	27.04±68.73	0.0005*	-21.13±67.55	
GA	Healthy subjects	2.22±1.43	2.45±3.39	0.4774	-0.22±3.97	0.0037 <sup>†</sup>
	Dizzy patients	3.57±3.29	7.83±8.77	0.0029*	-4.26±7.26	

EO, eyes-open; EC, eyes-closed; PCI, phase coordination index; GA, gait asymmetry.

Values are presented as mean±standard deviation.

\*Significant difference between the EO and EC conditions; <sup>†</sup>Significant difference between healthy subjects and dizzy patients.

## DISCUSSION

Balance is maintained even when the input from one or two sensory systems changes suddenly, such as when walking into a dark room or when walking on a soft, foamy surface. Sensory reweighting adjusts the relative contributions made by sensory systems based on the available sensory information. For example, impaired balance caused by proprioceptive loss can be detected by increased sway while standing with the EC in the Romberg test.<sup>20</sup> Intuitively, closing one's eyes during forward walking would be expected to slow walking speed, promote smaller steps, and render it more difficult to walk a straight line; our healthy subjects and dizzy patients both exhibited these features. We speculated that differences in gait parameters between the EO and EC conditions would be greater in dizzy patients, because deprivation of visual information would be more detrimental when vestibular information was already compromised. In other words, although walking would be more difficult under the EC condition than under the EO condition

for healthy subjects, dizzy patients may have difficulty walking even under the EO condition, difficulty that is increased under the EC condition. In accordance with our hypothesis, healthy subjects had slower walking speeds and smaller stride lengths than dizzy patients (Table 2). In comparison, dizzy patients showed slower walking speeds and smaller stride lengths under the EO condition, and speeds and stride lengths further decreased under the EC condition. Thus, we propose that the intrasubject differences between the EO and EC conditions may reflect the changes in spatiotemporal parameters and bilateral coordination parameters. Notably, only the difference-values in GA (i.e., not PCI or spatiotemporal parameters) varied significantly between the healthy subjects and dizzy patients. Gimmon, et al.<sup>8</sup> compared the PCI and GA values of controls, a vestibular dizziness group, and a non-vestibular dizziness group during walking under various visual conditions and reported a group difference only for PCI between the controls and the non-vestibular group. However, we found that PCI and GA values differed significantly between the healthy subjects and dizzy pa-



tients. It would not be appropriate to compare the results of these two studies directly, because our group of dizzy patients included patients with different types of vestibulopathies. Also, vestibular rehabilitation can compensate for functional impairment and, thus, improve walking in patients with peripheral vestibular disorders. Our dizzy patients reported that their daily activities were impaired, which may partially have been associated with increased gait instability. For instance, indeed, patients with dizziness typically have difficulty in maintaining their posture and in walking during the initial phase of acute unilateral vestibular dysfunction due to vestibular neuritis, but often recover over several days to weeks. In contrast, a patient with a slow-growing VS may experience subtle dizzy symptoms, but increased postural and gait instability. Thus, in future studies, it would be useful to test for correlations between gait parameters and the extent of vestibular impairment in patients with dizziness of various etiologies.

It is well-established that gait disturbances impair mobility and increase disability, fear of falling, and actual falls per se, thus reducing quality of life.<sup>1,21</sup> Because IMUs are small and light, they are useful for the evaluation of dizzy patients who present with gait disturbance.<sup>22</sup> Gait evaluation need not be limited to treadmills or a small room; testing should include challenging locations, such as slopes or stairways. For example, severe acute symptoms in a patient with acute vestibulopathy often hinder walking, even with EO, on a flat, firm surface. However, a well-compensated patient with chronic subjective dizziness experiences little difficulty in walking even with EC. IMUs can be applied under various conditions, as reported recently.<sup>10</sup> IMUs have been used for gait analysis in patients with acute vestibulopathy,<sup>12</sup> and several studies have used IMUs to analyze gait changes in response to visual input conditions.<sup>8,23</sup> Although direct comparisons of different study protocols are difficult, we believe exploration of diverse protocols should be explored for use in patients with dizziness to improve existing gait-analysis protocols. Notwithstanding, IMUs can be readily used in older populations to evaluate gait under various visual conditions when exploring fall risk during everyday activities, including when getting up during the night. Finally, IMUs can be used to evaluate gait under various visual input conditions during initial assessment and when checking a patient's progress during customized vestibular rehabilitation programs: accurate assessment is essential for appropriately tailored vestibular exercise regimens, and the exercises must be sufficiently challenging to promote vestibular compensation, but not overwhelming or unsafe.

The clinical course after acute vestibulopathy varies: some patients return to normal daily activities after a few days, while others suffer from persistent dizziness over several months. Although the extent of vestibular insult is presumably relevant, subjective symptoms do not necessarily correlate with the results of vestibular function tests.<sup>24</sup> Some patients experience particular difficulty at night, when insufficient vestibular compensa-

tion may limit sensory reweighting to information other than visual input. We thus surmised that intrasubject differences in the ability to maintain balance under EO and EC conditions might be clinically significant under both static and dynamic (walking) conditions. In this study, we examined intrasubject differences in gait parameters between dynamic EO and EO conditions. If our results reflect the severity of subjective symptoms of dizziness, the addition of simple gait assessment to vestibular rehabilitation programs for dizzy patients would provide valuable information substantiating subjective symptoms and facilitating the planning of customized exercise programs. Differences in gait parameters between the EO and EC conditions would be useful for ensuring that the difficulty of exercises is appropriate. Our results differ from those of Gimmon, et al.,<sup>8</sup> who reported significant differences in gait between healthy subjects and patients with central vestibular, but not peripheral vestibular, dysfunction, during walking with EO, EC, or the EO and EC intermittently. It was proposed that sensory reweighting differs between static and dynamic conditions, and is influenced by central processing. Our study design differed from those of previous studies in that we focused on intrasubject differences in gait parameters, because we suspected that dizzy patients often exhibit only subtle changes in gait parameters despite relatively serious balance difficulties. Additionally, Yelnik, et al.<sup>23</sup> showed that, in healthy subjects, walking was more difficult with EC than with EO, and even more so with EO while wearing black goggles. Further studies of patients with balance problems using various methods to manipulate visual cues, such as wearing goggles or using augmented reality techniques, will facilitate customization of vestibular rehabilitation programs.

The limitations of this study include the age difference between the healthy controls and dizzy patient groups. As aging affects the gait cycle, direct comparison between the two groups would be inappropriate; thus, we focused on individual differences in the variables. We compared the performance of the same individual between the EO and EC conditions to assess any difficulty in walking that might not have been readily apparent under the EO condition. It should be noted that our dizzy patient group differed in terms of their disease etiologies and dizziness severity. Future studies should evaluate the correlations of subjective difficulty experienced during daily activities and gait disturbance under various visual condition, and determine whether these vary by disease etiology.

In conclusion, GA was higher in patients with dizziness when walking under the EO condition. The addition of an EC test to the standard gait evaluation protocol would provide useful information on sensory reweighting during forward walking.

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## AUTHOR CONTRIBUTIONS

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