

# Change of Gait After Unilateral Vestibular Neuritis: A Prospective Longitudinal Observation Study

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## Research

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# Abstract

**Background:** Although symptoms of unilateral vestibular neuritis (uVN) resolve spontaneously and quickly, there are uncertainties in the recovery of gait function. There is lack of prospective longitudinal study for gait function after acute uVN. In addition, there is no report for longitudinal changes in medio-lateral stability during gait after uVN. Therefore, the present study tested time effects on spatio-temporal parameters and on the medio-lateral CoM-CoP relationship. In addition, we explored differences of gait metrics between uVN and controls.

**Methods:** This is a prospective longitudinal observation study. Of 122 participants with vestibular symptoms, 23 participants with uVN and 20 controls were included in data analysis. 3D gait analysis, dizziness handicap inventory (DHI) and computerized dynamic posturography (CDP) were conducted 3 times after uVN onset: the 1<sup>st</sup> test was conducted within 2 weeks after onset, 2<sup>nd</sup> test after 1 month of 1<sup>st</sup> test and 3<sup>rd</sup> test after 1 month of 2<sup>nd</sup> test. From gait analysis data, spatio-temporal parameters, inclination angle in frontal plane (IA) and variability of IA were obtained. Time effects on gait metrics were tested with linear mixed model.

**Results:** Walking speed improved significantly between the 1<sup>st</sup> and 3<sup>rd</sup> test but they were within normal range, even at the 1<sup>st</sup> test. Step width was significantly larger than control at the 1<sup>st</sup> test and improved to normal at the 2<sup>nd</sup> test. IA did not show significant difference between uVN and control. Variability of IA in the affected side was significantly larger than that in controls at the 1<sup>st</sup> test and improved significantly at the 3<sup>rd</sup> test compared to the 1<sup>st</sup> test.

**Conclusions:** Improvement of overall gait function and neural adaptation of medio-lateral stability during gait continued during recovery stage of uVN (after 2 months of onset). Vestibular rehabilitation for gait should be continued during recovery stage of uVN to enhance appropriate adaptation.

## Background

Acute stage of unilateral vestibular neuritis (uVN) lasts a few days to several weeks and has drastic consequences on balance control (1, 2). After acute stage of uVN, there is recovery of balance function by neuronal and behavioral plasticity (2, 3). The recovery of balance function occurs over weeks and months through the process of vestibular compensation: restoration, habituation and adaptation.

Gait is an essential body function for activity of daily living. Individuals with uVN have gait dysfunction because the vestibular system plays a critical role in the modulation of balance during gait (4, 5). The vestibular modulation of balance during gait is mediated through vestibulo-ocular reflex (VOR) and vestibule-spinal reflex. Patients with uVN can walk within 48 hours after onset, can be back to normal activities about 2 weeks and will be subjectively back to normal (6). However, recovery of postural stability is usually slower than that of gaze stability (7). Although dysfunction of vestibulo-ocular reflex (VOR) is underpinning of symptoms in uVN, there is conflicting evidence regarding relationships between

VOR recovery and gait function (5). These findings may result from involvement of vestibule-spinal reflex and vestibule-cortical circuit in balance control during gait. Weak correlations between VOR and gait function suggest that the gait function should be evaluated independently to the VOR recovery (8).

Gait dysfunction after uVN has been frequently assessed by clinical scales such as Berg Balance Scale, Timed Up and Go and Activieis-specific Balance Confidence Scale. Although clinical scales are easy to use, quick to perform and inexpensive, they are subjective, have ceiling effects, are not responsive to small changes and do not reflect the underlying mechanism of balance control (9). Therefore, to detect precise change of gait after uVN, it is necessary to assess gait dysfunction by quantitative parameters from instrumented gait analysis systems. Previous studies have reported differences of spatio-temporal parameters between vestibular disorders and healthy controls (10, 11). However, there is lack of reports which investigated longitudinal change of spatio-temporal parameters in uVN. In addition, spatio-temporal parameters have limitations in providing direct evidence for the biomechanical mechanism of balance control during gait.

Dynamic balance during gait can be assessed by the relationship between center of mass (CoM) and center of pressure (CoP) which provides information relevant to the biomechanical mechanism of balance control during gait. Unilateral vestibular dysfunctions usually show postural sway and tendency to fall toward the affected side during gait, which suggest more lateral displacement of CoM toward the CoP in the affected side. However, there is lack of reports for whether the CoM displaces more close to the CoP of the affected side in frontal plane after onset of uVN, compared to healthy controls. Although postural sway improves after acute stage of uVN, the extent and timing of improvement of sway are still unclear. Allum et al. reported that postural sway reached to normal range at 3 months (12). Halmagyi et al, postulated that increased body sway during walking remained about 3 months (6). These contrary findings suggest that it is also unclear when the recovery of CoM-CoP relationship in frontal plane occurs after uVN. Because balance control during gait, especially in frontal plane, is related with increased fall risk in uVN, revealing the characteristics of CoM-CoP relationship after uVN is clinically important to accurately figure out remaining gait dysfunction and to appropriately applicate vestibular rehabilitation.

The purpose of this study was to investigate the recovery of gait function after onset of uVN. We tested time effects on spatio-temporal parameters and on the CoM-CoP relationship and explored differences of gait metrics between uVN and controls.

## Methods

### Participants

This is a prospective study conducted in the Korea university Guro medical center. Of the individuals who visited department of otorhinolaryngology-head and neck surgery for acute vertigo and were referred to rehabilitation department for 3D gait analysis from January 2018 to January 2019, patients with uVN were included in the data analysis. Diagnosis of uVN was confirmed by otology specialist through

medical history, physical examination and clinical tests including bithermal caloric test; the canal paresis was defined by the response difference of 25% or more than between the ear. After diagnosis, education of vestibular ocular rehabilitation exercise was provided for recovery. Exclusion criteria of participants in the data analysis were 1) Meniere disease, recurrent vestibulopathy or benign-paroxysmal-positional-vertigo, 2) comorbidity in CNS such as cerebral infarction, 3) medical history of musculoskeletal problems that could disturb normal walking, such as joint contracture, severe peripheral neuropathy. Participants in the control group were recruited from physical medicine and rehabilitation department and they did not have neuromuscular disease disturbing gait, confirmed by one physiatrist. Informed consent was obtained from all participants with uVN and controls, and authorization and continued monitoring of the study protocol was obtained from the Korea university Guro medical center Institutional Review Board.

## Measurements

Perception and severity of dizziness were measured using the dizziness handicap inventory (DHI) at the first visit, 4 weeks, and 8 weeks. The DHI is a 25-item self-report questionnaire that assesses the impact of dizziness on daily life. Computerized dynamic posturography (CDP) (Smar Balance Master, NeuroCom international Inc., Portland, OR, USA) was conducted at 1st visit, 4 weeks and 8 weeks. From sensory organization test (SOT) of CDP, vestibular score and composite score were obtained (13, 14).

3D motion analysis for level walking was conducted within 2 weeks of initial visit to otology clinic when participants could walk independently. Motion analyses were repeated after 4 weeks and 8 weeks. The motion analysis laboratory has an 8 meter level walkway and force plates embedded in the middle of the walkway. The ground reaction forces were measured by two force plates (Kistler, Type 5233A, Switzerland) with 1200 Hz frequency. An optoelectronic motion analysis system (Qualysis, Qualisys Medical AB, Gothenburg, Sweden) with eight cameras (Oqus 500+, Qualysis Medical AB, Gothenburg, Sweden) was used to capture 3D trajectories of reflective markers at 120 Hz. Fifty-six reflective markers were attached on head, trunk, pelvis, arm, forearm, thigh, leg and foot segments recommended by Visual3D (C-motion Inc., Rockville, Maryland, USA) (Fig. 1). Explicit target was set parallel to the laboratory anterior-posterior axis to inform the target direction for participants during walking trials. Participants walked with self-selected speed. To ensure safety issues, the development of discomfort or fatigue were checked and walking tests were stopped when patients complained of fatigue or discomfort. More than 3 trials which had clear contact on the force plate were obtained.

## Gait Data Analysis

Visual3D software was used to calculate the temporospatial, kinematic, and kinetic parameters. Joint angles were computed relative to the proximal segment. The head and pelvis angles were the segment angles with respect to the global coordinate reference. Joint moment and power were calculated in the hip, knee and ankle. CoP during stance phase was calculated from force plate data for each side. CoM data were provided by Visual3D which calculated CoM from kinematics of segments and anthropometric data. CoM-CoP inclination angle (IA) was calculated in the frontal plane of global coordinate system

(Fig. 1). IA in the affected side (IA<sub>aff</sub>) and IA in the non-affected side (IA<sub>nonaff</sub>) were determined according to the side of uVN. IA was observed during stance phase which was normalized as 100%. Minimum value of IA (IA<sub>min</sub>) were obtained in each lower limb. Variability of IA (IA<sub>var</sub>) was calculated with normalized root mean squared error (NoRMS) (15–17) in each participant. Gait metrics from controls were averages of both sides.

## Statistics

Descriptive statistics for age, sex, lesion side were conducted. Independent sample t-test and chi-square test were used for the comparison between uVN and control. Linear mixed model (LMM) were used to investigate the time effect on DHI, vestibular score, composite score, and gait metrics in uVN. The LMM allow estimation of the effects of explanatory variables, fixed effects including time and side, while statistically controlling the effects of participants, random effects. This approach was implemented to investigate if there is a significant change in dependent variables across time (1st, 2nd and 3rd test) and side (affected vs non-affected). Fixed effect “side” was included when dependent variables are measured in the affected and non-affected side, separately. Multiple models were run and the likelihood-ratio test was used to investigate if introducing fixed effects fitted with maximum likelihood, while keeping the random effects structure the same. Therefore, the likelihood-ratio test via ANOVA was used to compare the goodness of fit of different models. R 3.32 statistical software (R foundation for statistical computing, 2016) was used for all statistical analyses. All models were fitted using the “lmer” function in R. R package “lmerTest” was used to compute least-squares means and pairwise differences of these and *p*-values (Kuznetsova et al., 2017). Independent t-test was used to explore differences of gait metrics between uVN and control groups. The required minimum sample size was calculated with a 5% significance level, 80% power, effect size 0.3, and 3 repetitions within factors by G\*Power 3.1.9.2 software. Statistical significance was set  $p < .05$ .

## Results

### General Characteristics of participants

Of the 122 participants referred for 3D gait analysis study, 27 participants were confirmed with uVN. Of 27 participants, 4 participants did not participated in follow up test and 23 participants with uVN were included in the data analysis. Control group included 20 healthy adults. General characteristics of participants are described in Table 1. There were no significant differences in age, height, weight and sex ratio between uVN and control group.

Table 1  
Comparison of general characteristics between uVN and control groups.

	uVN (n = 23)	Control (n = 20)	p-value
Age (years)	57.57 (11.60)	57.10 (9.64)	.89
Height (m)	1.61 (0.09)	1.62 (0.08)	.66
Weight (kg)	64.5 (14.52)	64.2 (11.3)	.94
Sex (female / male)	13 / 10	9 / 11	.65
Side of uVN (left / right)	7 / 16		
Comparisons between uVN and control were conducted with t-test and chi-square test. Values are means (SD). uVN: unilateral vestibular neuritis.			

## Changes in DHI, VEST and composite scores

The results of linear mixed model analysis with the likelihood-ratio test to compare the goodness of fit of different models were reported in Table 2. The time effect was significant fixed effect on DHI (chisq = 24.89,  $p < .01$ ), vestibular score (chisq = 8.22,  $p = .02$ ), and composite score (chisq = 10.28,  $p < .01$ ). Post-hoc analysis showed significant difference between 1st test and others (2nd and 3rd) in DHI, vestibular score and composite score (Table 3).

Table 2. Results from likelihood-ratio test via ANOVA to test the significances of time and side effect .

A. Model 1: DV = 1+(1|ID), Model 2: DV = 1+time+(1|ID)

DV = DHI	Df	AIC	BIC	logLik	Deviance	Chisq	Df	p
Model 1	3	615.61	622.31	-304.81	609.61			
Model 2	5	594.74	605.91	-292.37	584.74	24.868	2	<b>&lt; .01</b>
DV = vestibular score	df	AIC	BIC	logLik	Deviance	Chisq	Df	p
Model 1	3	625.17	631.88	-309.59	619.17			
Model 2	5	620.96	632.13	-305.48	610.96	8.2174	2	<b>.02</b>
DV = composite score	df	AIC	BIC	logLik	Deviance	Chisq	Df	p
Model 1	3	517.09	523.79	-255.54	511.09			
Model 2	5	510.81	521.98	-250.41	500.81	10.276	2	<b>&lt; .01</b>
DV = speed	df	AIC	BIC	logLik	Deviance	Chisq	Df	p
Model 1	3	-80.387	-73.685	43.194	-86.387			
Model 2	5	-83.177	-72.007	46.589	-93.177	6.7901	2	<b>.03</b>
DV = stride length	df	AIC	BIC	logLik	Deviance	Chisq	Df	p
Model 1	3	-109.89	-103.19	57.947	-115.89			
Model 2	5	-113.00	-101.83	61.502	-123.00	7.1112	2	<b>.03</b>
DV = cadence	df	AIC	BIC	logLik	Deviance	Chisq	Df	p
Model 1	3	494.56	501.26	-244.28	488.56			
Model 2	5	497.92	509.09	-243.96	487.92	0.6387	2	<b>.73</b>
DV = step width	df	AIC	BIC	logLik	Deviance	Chisq	Df	p
Model 1	3	-310.24	-303.54	158.12	-316.24			
Model 2	5	-312.50	-301.33	161.25	-322.50	6.2541	2	<b>.04</b>
Random effect structure with participants was retained (random intercept, 1  ID). DV is dependent variables and ID is participants. DHI: dizziness handicap inventory.								

B. Model 1: DV = 1+(1|ID), Model 2: DV = 1+time+(1|ID), Model 3: DV = time\*side+(1|ID)

DV = step length	Df	AIC	BIC	logLik	Deviance	Chisq	Df	p
Model 1	3	-449.51	-440.73	227.75	-455.51			
Model 2	5	-455.63	-441.00	232.82	-465.63	10.125	2	<b>&lt; .01</b>
Model 2	5	-455.63	-441.00	232.82	-465.63			
Model 3	8	-450.60	-427.19	233.30	-466.60	0.9716	3	.81
DV = stance phase	df	AIC	BIC	logLik	Deviance	Chisq	Df	p
Model 1	3	-719.39	-710.61	362.69	-725.39			
Model 2	5	-722.73	-708.09	366.36	-732.73	7.34	2	<b>.03</b>
Model 2	5	-722.73	-708.09	366.36	-732.73			
Model 3	8	-718.19	-694.77	367.09	-734.19	1.46	3	0.69
DV = swing phase	df	AIC	BIC	logLik	Deviance	Chisq	Df	P
Model 1	3	-719.39	-710.61	362.69	-725.39			
Model 2	5	-722.73	-708.09	366.36	-732.73	7.3402	2	<b>.03</b>
Model 2	5	-722.73	-708.09	366.36	-732.73			
Model 3	8	-718.19	-694.77	367.09	-734.19	1.4615	3	.69
DV = IA_min	df	AIC	BIC	logLik	Deviance	Chisq	Df	P
Model 1	3	575.54	584.32	-284.77	569.54			
Model 2	5	579.02	593.66	-284.51	569.02	0.5207	2	.77
Model 2	5	579.02	593.66	-284.51	569.02			
Model 3	8	579.16	602.57	-281.58	563.16	5.8649	3	.12
DV = IA_var	df	AIC	BIC	logLik	Deviance	Chisq	Df	P
Model 1	3	-47.986	-39.204	26.993	-53.986			
Model 2	5	-55.614	-40.978	32.807	-65.614	11.628	2	<b>&lt; .01</b>
Model 2	5	-55.614	-40.978	32.807	-65.614			
Model 3	8	-53.058	-29.640	34.529	-69.058	3.4438	3	.33
Random effect structure with participants was retained (random intercept, 1  ID). DV is dependent variables and ID is participants. IA: inclination angle in frontal plane. Var: variance. SS: single support phase.								

Table 3  
Changes in clinical measurements during repeated tests in uVN

	<b>1st test</b>	<b>2nd test</b>	<b>3rd test</b>	<b>p-value</b>	<b>Post-Hoc</b>
DHI	38.52 (24.94)	25.56 (20.26)	18.52 (19.69)	<b>&lt; .01</b>	<b>1st ≠ 2nd, 1st ≠ 3rd</b>
Vestibular score	48.04 (25.69)	60.39 (20.50)	62.86 (16.95)	<b>.02</b>	<b>1st ≠ 2nd, 1st ≠ 3rd</b>
Composite score	67.52 (12.45)	74.17 (7.78)	74.43 (8.57)	<b>&lt; .01</b>	<b>1st ≠ 2nd, 1st ≠ 3rd</b>
p-values are from the statistical test for the time effect on variables. Values are mean (SD).					
uVN: unilateral vestibular neuritis, DHI: dizziness handicap inventory					

## Changes in Temporo-spatial Parameters

Compared to the null model which had only random effect of participants, introducing fixed effect (time) significantly improve the fit of the model for dependent variables, speed (chisq = 6.79, p = .03), stride length (chisq = 7.11, p = .03), step width (chisq = 6.25, p = .04) and proportion of stance phase (chisq = 7.34, p = .03) (Table 2). Introducing side effect did not improve the fit of the model for step length, proportion of stance phase and proportion of swing phase. Post-hoc analysis showed significant differences between 1st and 3rd test in walking speed and stride length (Table 4). Step width showed significant difference between 1st test and others (2nd and 3rd test) (Table 4).

Table 4

Changes in gait metrics during repeated tests for uVN and comparison between uVN and control

	1st test	2nd test	3rd test	p-value	Post-Hoc	Control	t-test results
Speed (m/s)	1.09 (0.17)	1.14 (0.14)	1.16 (0.13)	.04	1st ≠ 3rd	1.15 (0.12)	
Stride length (m)	1.16 (0.13)	1.20 (0.14)	1.22 (0.12)	.03	1st ≠ 3rd	1.20 (0.07)	
Cadence (steps/min)	112.76 (13.74)	113.50 (6.46)	114.25 (8.17)	.73		115.08 (9.24)	
Step width (m)	0.12 (0.04)	0.11 (0.03)	0.11 (0.03)	.05	1st ≠ 2nd, 1st ≠ 3rd	0.10 (0.02)	1st ≠ control ,
Step length in affected(m)	0.59 (0.07)	0.60 (0.07)	0.61 (0.06)	.23		0.60 (0.03)	
Steplength in nonaffected (m)	0.58 (0.07)	0.60 (0.06)	0.61 (0.06)	.12		0.60 (0.03)	
Stance phase in affected (%)	63.11 (2.17)	62.01 (1.80)	62.21 (1.82)	.01	1st ≠ 2nd, 1st ≠ 3rd	62.14 (1.18)	
Stance phase in nonaffected (%)	62.58 (1.99)	62.00 (1.64)	62.27 (2.00)	.26		62.14 (1.18)	
Swing phase in affected (%)	36.69 (2.17)	37.98 (1.80)	37.79 (1.82)	.01	1st ≠ 2nd, 1st ≠ 3rd	37.85 (1.18)	
Swing phase in nonaffected (%)	37.42 (1.99)	38.00 (1.65)	37.73 (2.00)	.26		37.85 (1.18)	
IA_min in affected (deg)	2.41 (2.33)	2.18 (1.95)	2.77 (1.00)	.58		2.21 (0.53)	
IA_min in nonaffected (deg)	3.40 (2.25)	3.08 (2.30)	2.64 (1.06)	.32		2.21 (0.53)	1st ≠ control
IA_var in affected	0.57 (0.19)	0.43 (0.17)	0.41 (0.13)	< .01	1st ≠ 3rd	0.44 (0.14)	1st ≠ control
IA_var in nonaffected	0.53 (0.28)	0.52 (0.23)	0.43 (0.13)	.23		0.44 (0.14)	
p-values are from the statistical test for the time effect on gait metrics. T-test results describe significantly different groups between control and uVN at each time. T-test was conducted for control and each time, respectively. Values are mean (SD).							
uVN: unilateral vestibular neuritis, IA: inclination angle in frontal plane, var: variability, SS; single stance phase, min: minimum.							

## Changes in Inclination Angles

Compared to the null model which had only random effect of participants, introducing fixed effect (time) significantly improved the fit of the model for IA\_var in more affected side (chisq = 11.63,  $p < .01$ ) (Table 2). However, introducing fixed effect (side) did not improve the fit of the model for IA\_var. Post-hoc analysis showed significant difference between 1st and 3rd test in IA\_var in more affected side (Table 4).

## Comparison to controls

Exploration of gait parameters with comparison to the controls, are reported in Table 4. Step width showed significant difference with controls at 1st test. IA\_var showed significant differences with controls at 1st in more affected side.

## Discussion

In the present study, limitations in daily life after uVN was measured by DHI (18). In the present study, average of DHI (38.52) at the 1st test corresponded to the results of previous studies for acute uVN, ranging 37 ~ 45 (19–21). DHI improved significantly between the 1st and the 2nd test. Although DHI improved between 2nd and 3rd tests, difference was not statistically significant. The authors think that statistical insignificance between 2nd and 3rd test resulted from the large inter-personal variations. Considering DHI scores less than 5 in healthy controls (21) and improvement to near normal value after 6 months (20), These findings suggest that perception of limitation in daily life after uVN persists after 3 months of onset. The results of vestibular score and composite score from CDP showed significant improvements between the 1st and 2nd tests. Compared to the normal reference values (22), vestibular score and composite scores at the 2nd test in the present study improved to the values within one SD of normal reference values. These findings suggest early return of vestibular function or limitation of CDP which does not reflect medio-lateral stability in the present study.

Characteristics of gait with poor balance (23) or perceptive dizziness (24) are slow walking speed, short stride/step length, increased percentage of double support and stance phases, increased step width and increased spatio-temporal variability. Previous investigations for vestibular disorders demonstrated gait characteristics different to healthy controls; slow walking speed, reduced cadence, and short step length (10, 11). The present study focused on the longitudinal change of gait function after uVN which had relatively fast recovery of vestibular function but prolonged limitation in daily living activity or social participation. In the present study, walking speeds, stride length and cadence did not show significant differences between uVN and control at the 1st, 2nd and 3rd tests, respectively. These findings suggest that overall walking function represented by walking speed is within normal after acute stage of uVN. However, speed and stride length showed significant improvement between the 1st and the 3rd test. These findings suggest continuous improvement of overall walking function during recovery stage (2 weeks to 3 months). Participants with uVN showed wider step-width at the 1st test than the controls. Step-width improved significantly between the 1st and 2nd test, thereby showing no significant difference to the controls at the 2nd test. Step width is related with foot placement strategy in balance control by widening base of support. Above results suggest that widening of step width is a temporary compensation strategy occurring during early recovery stage. Participants with uVN did not show

significant difference of stance phase proportion, compared to the control. Although stance phase proportion in the affected side significantly improved between the 1st and 2nd test, it was within normal range, even at the 1st test. Increased stance phase proportion is also related with balance control by reducing swing phase which corresponds to single support phase of opposite side and is dynamically unstable. These findings also suggest that increased stance phase proportion is a temporary compensation strategy during recovery stage. From the gait metrics in the present study, widening of step width and increasing of stance phase proportion may be compensation strategies observed in the early recovery stage of uVN. Even after these compensation strategies subsides, improvement of overall walking function represented by walking speed continues during recovery stage. Although spatio-temporal metrics are reliable, easy to uptake and most frequently studied, they have limitations in providing direct evidence of biomechanical or motor control evidence of balance control.

For vestibular disorders, most previous studies using CDP reported the CoM-CoP relationship in sagittal plane without that in frontal plane. However, previous authors postulated that CoM-CoP relationship in frontal plane might be more relevant to gait stability than that in sagittal plane (25). Medio-lateral stability during gait is maintained when CoM and extrapolated CoM are controlled within the BoS. In the previous studies, the maximum horizontal separation distance between COM and COP during stance was reported to sensitively quantify gait instability in patients with bilateral vestibular hypo-function or cerebellar ataxia (26, 27). However, position of CoM close to the CoP was related with fall and excessive lateral momentum of CoM was identified in balance-impaired elderly (28). We think that increased distance between CoM and CoP during stance phase may result from the compensation related with widening of base of support.

In the present study, IA<sub>min</sub> in non-affected side at the 1st test was significantly larger than the control. This finding may results from postural sway to the affected side and increased step width in uVN. Although there was trend to decrease IA<sub>min</sub> in non-affected side, the time effect on this metric was not significant. The authors think that this statistical insignificance results from large variances. Therefore, future study should be conducted to confirm the result of the present study. There were no significant differences of IA<sub>min</sub> between control and the affected side of uVN at the 1st, 2nd and 3rd tests. These results suggest maintenance of relationship between CoM and CoP during recovery stage of uVN while the step width increases at the 1st test. This supports that the CoM-CoP relationship in frontal plane is dominant constraint for maintenance of gait. In addition to the foot placement strategy which is represented by step width, ankle strategy may also influence on the CoM-CoP relationship after onset of uVN. Therefore, future studies should be conducted to reveal the influence of ankle strategy on uVN.

In the present study, uVN showed significantly larger IA<sub>var</sub> in the affected side at the 1st study, compared to controls. In addition, IA<sub>var</sub> decreased significantly at the 3rd study in the affected side, compared to the 1st study. This finding indicates continuous improvement of variability during at least 2 months after uVN onset. Human motor performance is generated inherently 'noisy' nervous system which results from stochastic events at the level of ion channels, synapses, neurons and neural networks (29). After uVN, noise in nervous system increases, thereby increasing uncertainty and variability. It is widely

believed that motor control is optimized for current performance, and that variability that interferes with this goal should be minimized (30). In other view, variability in motor performance is a means of exploring motor spaces which reinforce motor learning (31). We think that increased variability after acute stage of uVN suggests existence of actively ongoing adaptation process in vestibular system. Therefore, this period is clinically significant for long term progress and more active rehabilitation should be provided, because vestibular rehabilitation interventions interact with the recovery mechanism during the critical plastic time window of internal reorganization processes (2).

This study has limitations. Gait metrics were not evaluated during acute stage of uVN due to safety issues, thereby making time differences between 3D gait analysis and other tests. Duration of follow up was too short to investigate complete recovery of participants. Sample size was small for the t-test to compare uVN and control results. Although education of vestibular ocular rehabilitation exercise was provided at acute stage of uVN, quantitative monitoring for this exercise program was not implemented. Future study with longer follow up, larger sample size and control of rehabilitation program should be conducted to verify the results from the present study.

## Conclusions

Gait metrics showed improvement during recovery stage of uVN. Sequentially, step width, proportion of stance phase, walking speed and variability of CoM-CoP relationship improved. These findings suggest that improvement of dynamic stability during gait continues after 2 months of uVN onset although walking speed and step width are within normal range. We believe that clinicians should make efforts to provide vestibular rehabilitation more than two months after uVN onset, thereby enhancing appropriate neural plasticity for dynamic stability during walking.

## List Of Abbreviations

uVN: unilateral vestibular neuritis

VoR: vestibulo-ocular reflex

CoM: center of mass

CoP: center of pressure

DHI: dizziness handicap inventory

CDP: computerized dynamic posturography

SOT: sensory organization test

IA: inclination angle

IA<sub>aff</sub>: IA in the affected side

IA<sub>nonaff</sub>: IA in the non-affected side

IA<sub>min</sub>: minimum value of IA

IA<sub>var</sub>: Variability of IA

NoRMSE: normalized root mean squared error

LMM: Linear mixed model

## **Declarations**

### **Ethics approval and consent to participate**

Informed consent was obtained from all participants with uVN and controls, and authorization and continued monitoring of the study protocol was obtained from the Korea university Guro medical center Institutional Review Board.

### **Consent for publication**

Not applicable

### **Availability of data and material**

The datasets generated or analysed during the current study are available from corresponding author on reasonable request.

### **Competing interest**

The authors declare that they have no competing interests.

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### **Authors' contributions**

S-W Chae: funding acquisition, conceptualization, project administration, review.

J-J Song: project administration, investigation, review.

W-S Kim: investigation, data analysis, writing original manuscript.

All authors read and approved the final manuscript.

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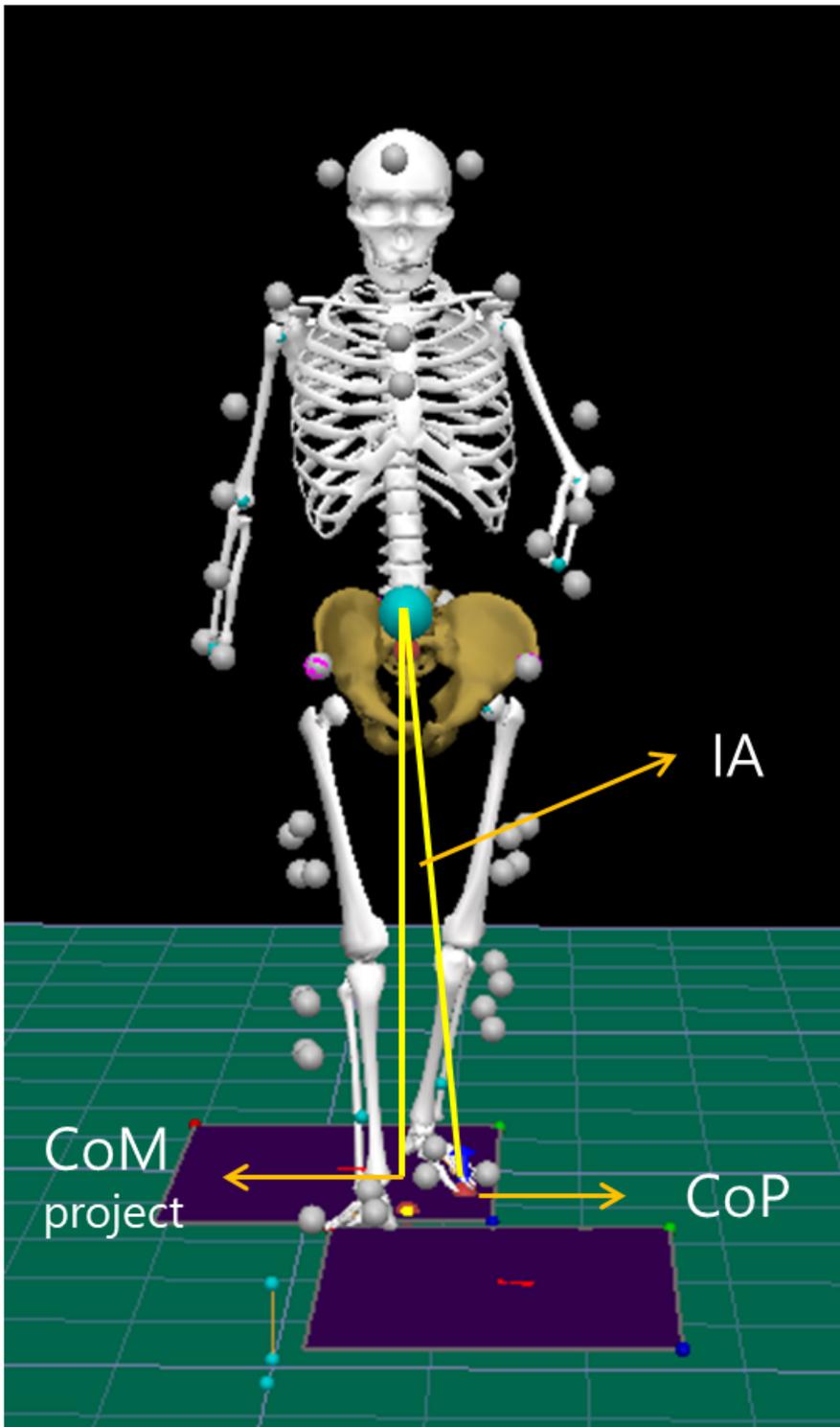
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## Figures



**Figure 1**

Fifty-six reflective markers were attached on head, trunk, pelvis, arm, forearm, thigh, leg and foot segments. Inclination angle (IA) was obtained with CoM, CoM projection on XY plane and CoP. Vector1 from CoM to CoM projection and vector2 from CoM to CoP were obtained. Angle between vector1 and vector2 was obtained with right hand rule by Visual3D. The angle obtained was projected to YZ plane (sagittal) and XZ plane (frontal). When CoM did not go lateral to the CoP in frontal plane, left limb IA was

positive sign and right limb IA was negative sign. Therefore, we changed right frontal plane IA sign by multiplication of (-1). IA: inclination angle, CoM: center of mass, CoP: center of pressure