# Instrumented Romberg Test of Postural Stability in Patients with Vestibular Disorders using Inertial Measurement Units

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Abstract— Impaired balance control is a common symptom of vestibular deficiencies. The Romberg test is one of the most commonly used balance tests in clinics. It allows clinicians to assess the subject's reaction posture control while standing. However, a positive Romberg test still relies on manual observation by the physician. It leads to technical issues in subjective evaluation during the test. The study aimed to propose an instrumented Romberg test using inertial measurement units (IMUs) to extract kinematic variables for objective assessment. Eighteen patients and thirteen healthy people participated in this study. They performed the Romberg test with their eyes closed, wearing IMUs at their head and pelvis. Six types of parameters are extracted from IMUs, such as maximum, average, and root mean square, Attenuation coefficients, sway velocity, and displacement. The results show that the patient group performed a larger sway in the lateral direction of head or pelvis level, where the maximum and RMS values have significant differences (p < 0.05) and large effect (Cohen's d > 0.8). The proposed approach can distinguish patients with vestibular dysfunction from healthy people and support objective clinical assessment.

# I. INTRODUCTION

Balance control consists of a complex feedback control system integrating visual, somatosensory, and vestibular input [1]. These sensory inputs transfer into body postural adjustments, keeping the body's center of mass in a balanced state [2]. Impaired postural control is a common consequence of vestibular system dysfunction [3]. This abnormal body control is associated with an increased risk of falls during activities of daily living.

Vestibular dysfunction is a common disease with a prevalence of approximately 35% in adults above 40 years old, and 85% of those 80 years of age and older during 2001–2004 in the US [4]. In 2016, 59,986 patients received a diagnosis of peripheral vestibular disorders in Taiwan, with a prevalence rate of 2,833.4 per 100,000 population [5]. In addition to abnormal balance, dizziness is also one of the common symptoms of patients with vestibular disease, making it difficult for patients to maintain orientation [6]. Therefore, the balance tests are important to assess the balance ability for screening patients with abnormal vestibular function,

estimating the risk of falls, and monitoring change over treatment. There are lots of assessment approaches for vestibular diseases, such as tests of vestibulo-ocular reflex (VOR), balance tests, and so on [7].

The Romberg test is one of the most commonly used balance tests in clinics, allowing clinicians to assess the subject's postural control while standing [8]. The measurements of the test usually include the subject's body sway amplitude and whether the test is completed or not. The Romberg test is easy, inexpensive, rapid to use in outpatient departments. However, a positive Romberg test still relies on manual observation by the physician. It leads to technical issues in subjective evaluation during the test.

In recent years, many studies have used different techniques to assist objective clinical assessments [9-11]. Body-worn inertial measurement units (IMUs) can measure movement patterns by sensing acceleration and angular velocity over time [12]. Various statistical and kinematic features extracted from IMUs can provide more information about movement performance and individual exercise strategies for supporting clinical examination and evaluation. With the advantages of portability, lightness, and low cost, these sensors also enable clinicians to obtain objective, effective, and reliable measures. IMUs are commonly used in screening studies and therapeutic interventions, such as in Parkinson's disease [9-10] or stroke [11]. Previous studies have utilized a single IMU to the Romberg test in different groups, including cerebellar ataxia [13-14] and frail elderly subjects [15]. However, few studies have examined multi-sensor Romberg assessment in vestibular patients.

The purpose of this study is to propose an instrumented Romberg test using multiple body-worn IMUs to measure and analyze movement patterns and postural control. Kinds of parameters based on IMU signals are estimated to quantify kinematic differences between patients with vestibular disorder and healthy people. The hypothesis is that these parameters could complement the traditional clinical assessment outcomes of the Romberg test.

### II. MATERIAL AND METHOD

# A. Participants

Two groups of participants were involved in this study: patient group (PG) and control group (CG). The patient group comprised eighteen patients (3 males and 15 females, age range: 27-79 years) recruited from the hospital otology and was diagnosed with unilateral or bilateral vestibular weakness. The diagnosis is confirmed by an experienced otologist after a series of supported clinical examinations, e.g., cervical vestibular evoked myogenic potential (cVEMP), caloric test. The control group was composed of thirteen healthy people (7 males and 6 females, age range: 21-32 years) recruited from the school, without neurological, orthopedic conditions. This study was approved by the institutional review board (IRB No.: 2021-04-006CC) of Taipei Veterans General Hospital. All participants were provided informed consent and entirely voluntary for their participation.

#### B. Experimental protocol

Two IMUs (Opal, APDM Inc., Portland, Oregon, USA) were used to record, process, and store accelerations and angular velocities data during the testing. Each unit contains a tri-axial accelerometer (range:  $\pm$  16 g with g = 9.81 ms<sup>-2</sup>) and a tri-axial gyroscope (range:  $\pm$  2000 °/s). To assess the stability of the upper body, one IMU was placed on the occipital cranium bone (H) and one at L4/L5 level, slightly above the pelvis (P), set by the adjustable straps (see Fig. 1) One camera was set up to record the video data during the testing. All devices were configured for synchronized recording, and the data were transmitted to the laptop in real-time via a wireless network at a sampling rate of 128 Hz.

Participants performed the Romberg test with their eyes closed. Initially, participants were instructed to stand upright on the rigid floor with their eyes closed and both arms crossed for at least five seconds. They started to maintain the balanced posture for 30 seconds when the clinical researcher starts timing. During the test, the clinical researcher stood near the participant to prevent falls.

# C. Data processing

The acceleration and angular velocity signals were disassembled according to the axes of the sensors and defined as three anatomical axes: cranio-caudal (CC), medio-lateral (ML), and antero-posterior (AP) axes, respectively corresponding to the x, y, z axes of the sensors. The tester



Fig. 1 The placement and the axes of the IMUs in the rear view.

labeled the beginning and ending of the Romberg test based on the recorded video. The determined sensing data were smoothed firstly using moving average to eliminate signal noise [16], and the average signal over the test was subtracted from the entire data series for normalization. Then, the first and last five seconds data series were removed to preserve a more continuous movement state.

For kinematic analyses, the following parameters were estimated from the IMUs signals at head and pelvis level, for each acceleration component *acceleration<sub>i</sub>*:

a) The maximum values of accelerations were obtained by (1).

$$\left(\forall x \in acceleration_i\right) x_{Max} \ge x \tag{1}$$

b) The mean values of accelerations were measured by (2).

$$mean_j = \frac{\sum acceleration_j}{samples}$$
(2)

c) The root mean square (RMS) of accelerations was calculated to take into account the different expected stability between patients and healthy people. High RMS values were associated with decreased stability. This variable is defined as (3).

$$RMS_{j} = \sqrt{\frac{\sum(acceleration_{j})^{2}}{samples}}$$
(3)

d) Attenuation coefficients (AC) represented the acceleration change from the pelvis to the head [17]. A positive (negative) value of AC means that the pelvis to the head becomes more and more stable (unstable). The variable is defined as (4).

$$AC_{j} = \left(1 - \frac{RMS_{j}^{H}}{RMS_{j}^{P}}\right)$$
(4)

e) Mean sway velocity (MV) was calculated by (5). The acceleration series were integrated, using the trapezoidal rule, to obtain the speed series, and then the average value is taken.

$$MV_j = \frac{\int acceleration_j}{samples} \tag{5}$$

f) Displacement (Disp.) was obtained by twice integration of the acceleration series, defined as (6).

$$Disp._j = \iint acceleration_j$$
 (6)

#### D. Statistical analysis

IBM SPSS statistical software version 24 was used for data statistical analysis. The  $\alpha$  level of significance was set at 0.05. An independent sample t-test was applied to check the difference between healthy people and vestibular patients in all variables. Then an effect size analysis was performed on the

parameters with significant differences (p < 0.05) using Cohen 's d value as a judgment, and screen out the parameters with high distinguishing effect (d > 0.8).

#### III. RESULTS

Each participant completed the Romberg test. Fig. 2 shows the acceleration signal on the ML axis of the pelvis, giving the visual information distinguishing between groups. The test outputs were collated as average and standard deviation (SD) values of two subject groups. The parameters related to segmental accelerations are shown in Table I. Whether at head or at pelvis level, the maximum, mean, and RMS values of accelerations showed no statistically significant difference on the CC axis and the AP axis, but the ML axis.

To see the correlation between the head and the pelvis, the results of AC are shown in Table II. The independent sample t-test showed no significant difference for AC parameters on any axis between the groups.

The results of the mean sway velocity and the displacement are shown in Table III. Similar to the results of Table I, the mean sway velocity and the displacement extracted from ML axis of head and pelvis have significant differences between groups.

Among the 36 parameters, 12 had significant differences (p < 0.05) in distinguishing patients from healthy people, and four of them, maximum acceleration and RMS on the ML axis at both head and pelvis, also met a large effect size (Cohen's d > 0.8) at the same time.



Fig. 2 The raw acceleration signals of the IMU sensor on the ML axis of the pelvis (A) of one of the healthy people and (B) of one of the patients.

Table I. The maximum, mean, RMS values of accelerations comparing between PG (N = 18) and CG (N = 13), reported mean (standard deviation).

	PG (SD)	CG (SD)	р	Cohen's d
Acceleration	pelvis			
Max <sub>CC</sub>	0.21 (0.38)	0.11 (0.03)	0.395	0.333
Mean <sub>CC</sub>	0.03 (0.02)	0.02 (0.01)	0.532	0.245
RMS <sub>CC</sub>	0.04 (0.03)	0.03 (0.01)	0.463	0.287
Max <sub>ML</sub>	0.29 (0.13)	0.2 (0.07)	0.016 *	0.808 §
Mean <sub>ML</sub>	0.07 (0.03)	0.05 (0.02)	0.018 *	0.796
RMS <sub>ML</sub>	0.09 (0.04)	0.06 (0.02)	0.016 *	0.817 §
Max <sub>AP</sub>	0.28 (0.20)	0.22 (0.06)	0.263	0.435
Mean <sub>AP</sub>	0.09 (0.07)	0.06 (0.02)	0.290	0.412
RMS <sub>AP</sub>	0.10 (0.08)	0.08 (0.02)	0.303	0.401
Acceleration	head			
Max <sub>CC</sub>	0.26 (0.38)	0.15 (0.06)	0.384	0.340
Mean <sub>CC</sub>	0.04 (0.04)	0.03 (0.01)	0.144	0.458
RMS <sub>CC</sub>	0.06 (0.06)	0.04 (0.01)	0.157	0.443
Max <sub>ML</sub>	0.49 (0.28)	0.27 (0.08)	0.005 *	0.887 §
Mean <sub>ML</sub>	0.10 (0.06)	0.06 (0.02)	0.042 *	0.771
RMS <sub>ML</sub>	0.14 (0.08)	0.08 (0.02)	0.010 *	0.810 §
Max <sub>AP</sub>	0.50 (0.57)	0.40 (0.18)	0.573	0.221
Mean <sub>AP</sub>	0.13 (0.12)	0.12 (0.08)	0.852	0.073
RMS <sub>AP</sub>	0.17 (0.16)	0.15 (0.09)	0.741	0.130

\*: p < 0.05, §: Cohen's d > 0.8

## IV. DISCUSSION

This study aimed to develop a rapid and valid technique to screen vestibular weakness. The results demonstrate that the Romberg test using IMUs can provide motion and movement information for clinical analysis. The proposed instrumented Romberg test allows clinicians to objectively measure body sway and posture control during stance. The parameters estimated from the test supplied detailed information about the patient-specific standing state, supporting the test to be used as a screening tool for patients with vestibular weakness.

The results of this study show that patients with vestibular disorder are more unstable than others when standing without visual cues. Most values of parameters extracted from the patient group are larger than those from healthy people. Especially, the extracted features on the ML axis of the head and the pelvis can provide more information for differentiating healthy and patient groups. Fig. 2 shows that the patients' lateral acceleration amplitude is larger than which of healthy people. The maximum and RMS features of accelerations were the most effective indicator, meeting a large effect size of Cohen's d value. All parameters extracted on the CC and AP axes have no statistically significant difference between the groups.

Table II. The AC values comparing between PG (N = 18) and CG (N = 13), reported mean (standard deviation).

	PG (SD)	CG (SD)	р	Cohen's d
CC axis	-0.82 (1.11)	-0.41 (0.49)	0.190	-0.433
ML axis	-0.56 (0.53)	-0.40 (0.27)	0.371	-0.349
AP axis	-0.59 (0.62)	-0.84 (0.80)	0.345	0.368

Table III. The MSV and the displacement variables comparing between PG (N = 18) and CG (N = 13), reported mean (standard deviation).

	PG (SD)	CG (SD)	р	Cohen's d
MV pelvis			-	
CC axis	0.25 (0.19)	0.21 (0.06)	0.493	0.269
ML axis	0.68 (0.3)	0.47 (0.18)	0.023 *	0.768
AP axis	0.85 (0.58)	0.62 (0.18)	0.213	0.483
MV head				
CC axis	0.43 (0.39)	0.28 (0.08)	0.108	0.504
ML axis	1.01 (0.57)	0.63 (0.16)	0.014 *	0.78
AP axis	1.25 (1.01)	1.19 (0.74)	0.874	0.062
Displacemen	t pelvis			
CC axis	5.07 (3.89)	4.23 (1.24)	0.493	0.269
ML axis	13.54 (5.94)	9.32 (3.51)	0.023 *	0.768
AP axis	16.96 (11.58)	12.35 (3.61)	0.213	0.483
displacemen	t head			
CC axis	8.67 (7.71)	5.5 (1.62)	0.108	0.505
ML axis	20.24 (11.33)	12.61 (3.16)	0.014 *	0.78
AP axis	24.92 (20.28)	23.79 (14.83)	0.874	0.062

\*: p < 0.05, §: Cohen's d > 0.8

AC represent the relationship between the stability of head and pelvis. Some studies believe that people with vestibular dysfunction lose their capability of controlling their heads keeping stable [18]. During dynamic movements suchas walking, the acceleration from low to high level of patients' upper body will gradually increase. This study demonstrates that this situation is not suitable for static standing. The AC variables extracted on any axis have no significant difference, showing that each subject adopted a different postural control strategy while standing.

This study applies IMUs to measure the movement of head and pelvis, while most studies about the Romberg test only focused on the pelvis movement [11]. The results show that the degree of swing at head level is found larger than that at pelvis level among all patients. It indicates the kinematic features extracted from the head are also important indicators for the assessment of vestibular diseases.

One main limitation of our study is the small sample size of the two subject groups (patients and healthy people). The current results may be affected by the number of participants. We need to recruit more subjects to make the research more complete. Another limitation is that there is a statistically significant difference in age between the two groups. It may affect the stability of the posture.

In order to provide more information about patients' balance control strategies, inertial sensors can be used in different balance tests in future studies, such as the Fukuda stepping test, the tandem walking test. The integration of these balance evaluation parameters is valuable for supporting clinical decision making and treatment strategies.

#### V. CONCLUSIONS

In conclusion, the present study shows that the instrumented Romberg test using IMUs can assist clinicians in obtaining objective information about motor control ability. The extracted features from IMUs can differentiate healthy and patient groups. In future work, we will recruit more subjects to increase the number of research samples, allowing the study for an investigation into patients with different kinds or severities of vestibular diseases.

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