

Walking Stability in Patients With Benign Paroxysmal Positional Vertigo: An Objective Assessment Using Wearable Accelerometers and Machine Learning

Yuqian Zhang

Shanghai Jiao Tong University

He Wang

Shanghai Jiao Tong University

Yifei Yao

Shanghai Jiao Tong University

Jianren Liu

Shanghai Ninth People's Hospital, Shanghai Jiao Tong University School of Medicine

Xuhong Sun

Shanghai Ninth People's Hospital, Shanghai Jiao Tong University School of Medicine

Dongyun Gu (✉ dongyunguj@163.com)

Ninth People's Hospital Shanghai Jiao Tong University School of Medicine <https://orcid.org/0000-0001-8011-6078>

Research

Keywords: Benign paroxysmal positional vertigo, Walking stability, Gait analysis, Wearable sensors, Machine learning model.

Posted Date: October 27th, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-94351/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Version of Record: A version of this preprint was published at Journal of NeuroEngineering and Rehabilitation on March 31st, 2021. See the published version at <https://doi.org/10.1186/s12984-021-00854-y>.

Abstract

Background: Benign paroxysmal positional vertigo (BPPV) is one of the most common peripheral vestibular disorders leading to balance difficulties and increased fall risks. This study aims to investigate the walking stability of BPPV patients in clinical settings and propose a machine-learning-based classification method for determining the severity of gait disturbances of BPPV.

Methods: Twenty-seven BPPV outpatients and twenty-seven healthy subjects completed level walking trials at self-preferred speed in clinical settings while wearing one accelerometer on the head and one on the lower trunk. Temporo-spatial variables and six walking stability related variables (root mean square (RMS), harmonic ratio (HR), gait variability, step/stride regularity, and gait symmetry) derived from the acceleration signals were analyzed. A support vector machine model (SVM) based on the gait variables of BPPV patients were developed to classify the BPPV severity of gait disturbances.

Results: The results showed that BPPV patients employed a conservative gait and significantly reduced walking stability compared to the healthy controls. Significant different mediolateral HR at the lower trunk and anteroposterior step regularity at the head were found in BPPV patients among mild, moderate, and severe DHI (dizziness handicap inventory) subgroups. SVM classification achieved promising accuracies with area under the curve (AUC) = 0.87, 0.80, and 0.95 respectively for classifying the three stages of DHI subgroups.

Conclusions: Results suggested that the proposed gait analysis that is based on the coupling of wearable accelerometers and machine learning provides an objective approach for assessing gait disturbances and handicapping effects of dizziness imposed by BPPV.

Trial registration: The trial was registered in the Chinese Clinical Trial Registry (<http://www.chictr.org.cn>) on March 29, 2018. Registration number: ChiCTR1800015432 (<http://www.chictr.org.cn/showproj.aspx?proj=25587>).

1. Introduction

Benign paroxysmal positional vertigo (BPPV) is considered to be the most common peripheral vestibular disorder with a lifetime prevalence of 2.4% [1]. The vestibular system senses the linear and angular acceleration of the head during movement, and this plays a critical role in stabilizing gaze, head, and trunk during movement in order to maintain balance. Due to the impaired vestibular system in BPPV, patients usually suffer from transient vertigo and nystagmus leading to balance difficulties, increased risk of falls, and generally reduced quality of life [1, 2].

The Dix-Hallpike test is regarded as the gold standard diagnostic test for BPPV. It is performed by moving the patient position to trigger nystagmus, based on which disease severity can be evaluated [3]. However, the sensitivity of this test for BPPV diagnosis is only 79.3%, which should be improved for making precision and accurate clinical decisions [4]. The Dizziness Handicap Inventory (DHI), a 25-item self-

assessment scale designed to measure the self-perceived level of handicap associated with the symptom of dizziness, has been proposed to assist in the diagnosis of BPPV and quantify the handicapping effects of dizziness in vestibular disorders [5, 6]. Previous studies have shown that there are significant differences in DHI scores between healthy people and BPPV [5, 7]. However, DHI is based on self-perception of disease and therefore there is still a lack of an objective tool to assess the severity of BPPV disease associated with dizziness handicapping.

Walking is a precision task and highly related to dynamic balance ability, which requires the maintenance of a stable gaze as well as a stable head and trunk movement to avoid falls. However, a stable gait remains a challenge in BPPV due to their impaired vestibular system. Previous studies have evaluated the walking performance of BPPV patients during normal gait and tandem walk, and impaired temporospatial variables were observed in these studies [8–10]. These results could only indicate a conservative gait adopted in BPPV to avoid falls but could not answer why they are still at high risk of falling. Another limitation of previous studies is that the measurement was conducted in laboratory settings and required sophisticated equipment such as 3D motion capture system, which could not truly reflect the gait disturbances during transient vertigo in BPPV patients.

Walking stability during natural walking have been used to quantify the balance ability and disease severity, which can be accessed using wearable sensors without the limitations of a gait laboratory environment [11–13]. The sensor-based measurements of walking stability include root mean square (RMS), harmonic ratio (HR), gait variability, gait symmetry and gait regularity [14]. Previous studies have found that BPPV patients have impaired abilities in controlling static posture balance in mediolateral and anteroposterior axes [15, 16], analyzing the walking stability in various axes rather than purely studying the temporospatial gait variables may help us to gain insights about the BPPV disease. Furthermore, previous studies have found the significant associations between the vestibular dysfunction and the changes of gait and balance, thus offering a possibility to objectively assess the severity of gait disturbances imposed by BPPV disease [17–19].

Therefore, the aim of this study was to quantitatively analyze the walking stability of patients with BPPV using accelerometers in clinical settings, and further to explore a method for the assessment of handicapping effects of dizziness imposed by BPPV. We hypothesized that patients with BPPV would exhibit impaired walking stability compared with healthy controls even if a conservative gait was adopted. We further hypothesized that the impaired gait variables are association with the DHI scores, and a machine learning-based model may objectively assess the handicapping effects of dizziness imposed by BPPV.

2. Materials And Methods

2.1 Subjects

Twenty-seven outpatients diagnosed with active, idiopathic unilateral BPPV of the posterior semicircular canal between the ages of 30 to 70 years (average 56.513.1), and twenty-seven healthy subjects between

the ages of 25 to 70 years (average 56.110.8) were included in this study (Table 1). None of the healthy subjects had any medical history of neurological or orthopaedic conditions. According to the classification of patient's functional abilities by DHI scores, the BPPV patients were classified into three subgroups: mild stage (DHI = 0–30), moderate stage (DHI = 31–60), and severe stage (DHI = 61–100).

The procedures of this study were approved and mandated by the institutional human research ethics committee of School of Biomedical Engineering, Shanghai Jiao Tong University (protocol number:201807), and conformed to the 1964 Helsinki Declaration. All subjects were fully informed of the study procedures, possible risks, privacy, and the freedom to withdraw. Informed consent was obtained from all participants.

2.2 Experiment setup

Level walking experiments were performed in the outpatient corridor of the neurology department at the Shanghai Ninth People's Hospital. All subjects were instructed to walk at self-preferred speed along a 20 m walkway, during which their head was not allowed to turn, eyes looking straight ahead, and arms swinging naturally. A Timing Gait System (Brower, Draper, Utah, USA) was used to measure the walking duration of the middle 10 m of steady walk. The trial was defined as invalid if the standard deviation of the walking duration of each subject exceeded 5%. In this study, 6 valid trials were obtained for each subject. Two accelerometers (Delsys, Inc., Boston, MA, USA) were firmly strapped on the subject's head and lower trunk at the third lumbar spinous process (L3) with belts (**Fig. 1**). Calibration was performed before each walking trail by placing it align with each orthogonal axis vertically to ensure the vertical acceleration is statically the $\pm 1g$ value. Acceleration signals were captured by Delsys acquisition software (Delsys, Inc., Boston, MA, USA) and recorded at 148 Hz sampling rate in three orthogonal axes (VT, AP, and ML), respectively.

2.3 Data processing and gait variable calculation

The gravity component was first removed from the raw acceleration data and then filtered with a second-order Butterworth low pass filter with a cutoff frequency of 22 Hz. Five clinically relevant temporospatial variables and six variables reflecting walking stability were selected and calculated in Matlab (2019 a, the MathWorks, Inc., Natick, MA, USA).

Temporo-spatial variables: *walking speed (m/s)*, walking distance (10 m) divided by the total time duration measured by timing gait system in the distance; *step length(cm)*, walking distance (10 m) divided by the number of steps; *cadence(steps/min)*, the number of vertical lower trunk acceleration peaks divided by the walking duration of each trial; *step timing variability*, SDs between successive gait cycles over an entire walking trial. Gait cycles were determined by the vertical lower trunk acceleration peaks.

Walking stability variables: Each variable in this part was calculated in the anteroposterior (AP), mediolateral (ML), and vertical (VT) axes. *Acceleration root mean square (RMS)*, the dispersion of the

measured acceleration signal relative to zero; *Harmonic Ratio (HR)*, the ratio of even harmonics and odd harmonics of the measured acceleration signal, reflecting the gait smoothness and symmetry [20]; *Step regularity (SR1)*, the amplitude of the first peak in the acceleration autocorrelation signal; *Stride regularity (SR2)*, the amplitude of the second peak in the acceleration autocorrelation signal; *Gait symmetry*, the closeness of SR1/SR2 to 1.0 [21]; *Gait variability*, the width of the dominant peak in the power spectrum of the measured acceleration signal [14].

2.4 Statistical Analysis

All statistical analyses were performed using SPSS Release 22 (SPSS Inc., Chicago, IL, USA). All continuous variables were described with mean \pm standard deviation. The normality test was performed using the Kolmogorov-Smirnov test and variables with positively skewed distributions were \log_{10} transformed before inferential analysis. Walking stability variables were first adjusted to walking speed to remove the influence of gait speed [22,23]. One-way ANOVA was performed to test the differences of gait variables between BPPV patients and healthy controls.

2.5 Classification model of BPPV severity

A machine-learning based model was built for the classification of DHI subgroups of BPPV disease automatically.

Feature selection: To improve the performance of classification model, the gait variables that showed significant differences between BPPV patients and healthy controls were used as feature selection set for BPPV severity classification model. One-way ANOVA was used to further identify the model features by analyzing the significant differences of the gait variables among three disease stages of BPPV by DHI scores.

Model training: Support vector machine (SVM) with a linear kernel was used to build the model due to its good performance with high dimensional data, high signal to noise ratio [24], and it outperformed other machine learning algorithms, i.e. multi-layer perceptron and the k-nearest neighbors in training gait data [25].

Model validation: Repeated 5-fold cross-validation was performed to evaluate the model performance, meaning that the dataset was split into 5 subsets, where 4 subsets were used for training the model and the remaining subset was used as an independent validation set. This training and validation were repeated 5 times where each time a different independent validation set was used. The receiver operating characteristic (ROC) curve and accuracy (AUC) were used to evaluate the model performance in each fold.

3. Results

3.1 Participant characteristics

Demographic characteristics of the 27 BPPV patients and 27 healthy subjects are shown in Table 1. The experimental groups were of similar age, weight, height, and gender ratio ($p > 0.05$).

Table 1
Mean value and standard deviation of subject characteristics.

	BPPV (n = 27)	Controls(n = 27)	p-value
Age (year)	56.5 ± 13.1	56.1 ± 10.8	0.63
Gender	16F + 11M	21F + 6M	0.28
Weight (Kg)	63.5 ± 10.8	59.6 ± 8.0	0.11
Height (cm)	162.0 ± 6.7	161.2 ± 5.1	0.45

3.2 Gait variables

Gait variables highlighted significant alternation in temporospatial characteristics and walking stability between healthy subjects and individuals with BPPV (Table 2). Compared to healthy subjects, BPPV patients walked more slowly with decreased cadences and shorter step lengths ($p < 0.05$) (Table 2). The RMS of BPPV patients were found generally decreased than that of healthy subjects, but the significant difference was found only in the VT axis of both head and lower trunk. There was no significant difference in the ML axis of both head and lower trunk between healthy people and individuals with BPPV ($p > 0.05$) (Table 2). In AP axis, although RMS in the head of BPPV patients was significantly lower than that of healthy subjects, there was no statistical significance in the lower trunk ($p > 0.05$) (Table 2). With regard to the HR, BPPV patients was generally lower than that of healthy subjects, and there was statistical significance in the ML axis of both head and trunk and the VT axis of the lower trunk (Table 2).

Table 2
Gait variables between BPPV patients and healthy subjects

Variables			BPPV	Controls	P-Value
Temporospatial	Walking Speed (m/s)		1.12 ± 0.15	1.20 ± 0.12	0.048
	Step length (cm)		75.78 ± 8.43	78.84 ± 5.86	0.043
	Cadence(steps/min)		111.17 ± 10.69	119.54 ± 8.03	0.002
	Step timing variability		0.018 ± 0.009	0.016 ± 0.006	0.38
RMS	Head	VT	0.178 ± 0.05	0.212 ± 0.04	0.02
		ML	0.11 ± 0.04	0.13 ± 0.03	0.09
		AP	0.13 ± 0.04	0.17 ± 0.03	< 0.01
	Trunk	VT	0.18 ± 0.06	0.22 ± 0.05	0.02
		ML	0.11 ± 0.03	0.10 ± 0.02	0.57
		AP	0.07 ± 0.03	0.09 ± 0.04	0.06
HR	Head	VT	2.66 ± 0.86	3.09 ± 0.88	0.50
		ML	2.18 ± 0.54	2.78 ± 0.66	0.04
		AP	2.07 ± 0.48	2.48 ± 0.63	0.15
	Trunk	VT	2.54 ± 0.74	2.98 ± 0.61	< 0.01
		ML	2.59 ± 0.72	2.97 ± 0.77	0.02
		AP	1.50 ± 0.55	1.74 ± 0.59	0.14

RMS refers to root mean square; HR refers to harmonic ratio; VT, ML, and AP refer to the vertical axis, mediolateral axis, and anteroposterior axis, respectively.

When assessing the walking stability from the perspective of gait quality, decreased consistency of gait was found in BPPV patients, as detected in the lower step regularity in all three axes at the head ($p < 0.05$), lower stride regularity in the VT axis at the head ($p < 0.05$), reduced symmetry in the ML axis at the lower trunk ($p < 0.05$) (Fig. 2). The gait variability known as another marker for walking stability was found increased in BPPV patients in the ML and AP axes at the head, and in the VT and AP axes at the lower trunk, compared to healthy subjects ($p < 0.05$) (Fig. 2).

3.3 Classification model of BPPV disease

BPPV patients were assigned to the mild (DHI = 0–30), moderate (DHI = 31–60) and severe (DHI = 61–100) subgroups according to their DHI scores (Table 3). Age and gender did not show significance differences among three DHI subgroups ($p > 0.05$).

Table 3

Demographics and gait variables among three DHI subgroups. Data are presented as median (First quartile)

Variables		Mild (N = 12)	Moderate (N = 9)	Severe (N = 6)
		DHI 0–30	DHI 31–60	DHI 61–100
Subject characteristics	Age (year)	62 (39.75)	63(47)	53.5(49.25)
	Gender	3M + 9F	5M + 4F	3M + 3F
	Weight (Kg)	62(59.25)	60(56)	56.5(52)
	Height (cm)	161(158.5)	160(156)	159(156.5)
Temporospatial variables	Step length	73.18(69.83)	80.57(76.68)	75(69.67)
	Cadence	114.06(107.53)	111.75(104.07)	116.11(96.48)
	Walking speed	1.10(1.01)	1.15(1.06)	1.19(0.97)
RMS	Head, VT	0.16(0.15)	0.17(0.16)	0.21(0.11)
	Head, AP	0.13(0.12)	0.14(0.12)	0.11(0.09)
	Trunk, VT	0.18(0.15)	0.17(0.15)	0.19(0.14)
HR	Head, ML	1.86(1.55)	2.00(1.47)	1.60(1.56)
	Trunk, VT	2.31(1.86)	2.13(1.77)	2.09(1.99)
	Trunk, ML**	2.50(2.17)	2.40(2.10)	1.76(1.58)
Step Regularity	Head, VT	0.69(0.65)	0.62(0.53)	0.62(0.57)
	Head, ML	0.61(0.55)	0.69(0.48)	0.47(0.23)
	Head, AP*	0.87(0.81)	0.84(0.75)	0.82(0.76)
Stride Regularity	Head, VT	0.78(0.73)	0.80(0.78)	0.76(0.73)
Gait Symmetry	Trunk, ML	0.90(0.84)	0.88(0.86)	0.91(0.74)
Gait Variability	Head, ML	0.77(0.72)	0.85(0.79)	0.81(0.73)
	Head, AP	0.79(0.73)	0.78(0.77)	0.80(0.73)
	Trunk, VT	0.76(0.72)	0.79(0.78)	0.76(0.74)

DHI refers to DHI score. VT, ML, and AP refer to the vertical axis, mediolateral axis, and anteroposterior axis, respectively. * indicates $p < 0.05$. ** indicates $p < 0.01$.

Variables	Mild (N = 12)	Moderate (N = 9)	Severe (N = 6)
	DHI 0–30	DHI 31–60	DHI 61–100
Trunk, AP	0.77(0.72)	0.78(0.76)	0.81(0.73)

DHI refers to DHI score. VT, ML, and AP refer to the vertical axis, mediolateral axis, and anteroposterior axis, respectively. * indicates $p < 0.05$. ** indicates $p < 0.01$.

Based on the gait analysis between BPPV patients and healthy control group (Table 2 and Fig. 2), gait variables with significant differences were selected as feature selection set for BPPV severity classification model (Table 3). One-way ANOVA results for these variables found HR in the ML axis at the lower trunk and step regularity in the AP axis at the head showed significant differences among the three subgroups ($p < 0.05$), thus these two variables were selected as features to build the SVM classification model (Table 3). The SVM model achieved AUCs of 0.87, 0.80 and 0.95 for mild, moderate and severe DHI subgroups identification, respectively. The ROC curve is shown in Fig. 3.

4. Discussion

To the best of our knowledge, this is the first study to analyze the walking stability of BPPV patients in clinical settings using wearable sensors. Results showed that patients with BPPV have significantly impaired walking stability even though a conservative gait was adopted. Furthermore, a SVM machine learning model based on two significant impaired walking stability variables automatically classified the handicapping effects of dizziness imposed by BPPV disease according to DHI scores, with average accuracy of 0.87, 0.80, and 0.95 for mild, moderate, and severe subgroups, respectively.

In the current study, we found that BPPV patients exhibited significantly lower walking speed, step length, and cadence indicating their conservative gait during vertigo onset, which were consistent with previous findings [8, 9]. The conservative gait might be the compensation to the ineffective sensory organization and abnormal vestibulospinal output caused by impaired vestibular information and can be seen as a compensatory strategy to enhance the dynamic stability during walking and thus avoid falls [26].

The walking stability analysis of BPPV patients showed that the RMSs in ML axis of both head and trunk did not decrease significantly with slower gait speed. Previous studies have reported that instability during walking is primarily in the ML and decline in ML stability is a major risk factor of fall [27, 28]. The RMSs of acceleration in ML axis is often employed as an index to evaluate the walking stability and higher RMS is generally associated with higher postural disturbance and risk of falls [29, 30]. Thus, our findings reveal that patients with BPPV were not able to attenuate the ML and AP axes acceleration in a tolerable level to maintain a stable visual field and postural stability, which may explain the reason that BPPV patients still have high fall risks despite employing this more conservative strategy.

In the presented study, the lower HRs at the lower trunk in the VT and ML axis were found in BPPV patients while they walk at self-preferred speed. HRs has been used as a stability index to evaluate the smoothness of gait and higher HRs are interpreted as greater walking smoothness [31, 20]. Previous

studies have applied the HRs from trunk acceleration data to assess the stability of the trajectory of the center of mass and investigated the balance control ability between older adults, individuals with Parkinson's disease, and individuals with sensory impairment [32–34]. Consistence with previous studies, our findings suggest that the peripheral vestibular disorder in BPPV patients has affected their walking smoothness and balance control.

We also identified the alternation in the walking stability of BPPV patients from the perspective of gait quality. The significant lower step regularity, stride regularity and gait symmetry were found in BPPV patients, suggesting that patients are less able to regulate the repeated walking pace and to control the rhythmic displacements of the body during walking. Furthermore, we found significant higher gait variability in BPPV patients compared to healthy subjects, which was consistent with previous studies that patients with vestibular failure had increased variability during slow walking [35]. Gait variability has been investigated as a very important objective variable in differentiating patients with balance problems and increased gait variability were found strongly associated with higher risk of fall [36]. Thus, our finding demonstrates that the gait and balance disturbances are the main symptoms of BPPV patients which could be objectively assessed by sensor- based walking stability parameters.

DHI is a validated tool to evaluate the handicapping effects of dizziness in vestibular diseases. Previous studies have found that BPPV in general was associated with relatively higher DHI scores, indicating that BPPV patients are suffering from considerable dizziness handicap [37–39]. However, there was no association between dizziness handicap and the intensity of positional nystagmus during BPPV diagnostic maneuvers [39], and therefore there is still lack of an objective tool to diagnosis the handicapping effects of BPPV disease. In this study, we found significant walking stability impairments shown by mediolateral HR at lower trunk and anteroposterior step regularity at head among mild, moderate and severe of DHI subgroups, while temporospatial parameters were no significant differences. These results proved our hypothesis that the gait disturbances imposed by the dizziness/vertigo in BPPV patients are mainly reflected in the balance function even if they adopt a conservative gait. Since DHI is a self-reported questionnaire to quantify the dizziness on a daily basis[37], we built a machining learning-based model to classify different DHI subgroups with good performance, providing an objective method for assessing and monitoring the handicapping effects of dizziness imposed by BPPV disease.

There were several limitations in this study. First, we only recruited the patients with posterior canal BPPV, thus the results may not be applied to the BPPV patients with other types (i.e. horizontal canal). Second, the subjects included in three DHI rating subgroups have a relatively small sample sizes, thus only two walking stability variables were found significant differences among the three severity level groups. Third, we utilized SVM algorithm to classify the DHI rating groups of BPPV as a preliminary attempt to assess the disease severity and progression. A future research direction would be to investigate the posterior and lateral canal patients and to develop more efficient algorithms to assist in the diagnosis of BPPV disease.

5. Conclusions

The study found that BPPV patients have impaired walking stability even though a more conservative gait is adopted. The wearable technology provides a promising way to assess the gait disturbances in BPPV disease in the clinical settings. Using the impaired walking stability characteristics of BPPV patients, a machine learning-based classification model can be used to objectively assess the handicapping effects of dizziness imposed by BPPV with promising performance. The study set the stage for future development of wearable technology in tracking of gait and balance disorders, and could serve to inform future interventions in BPPV disease.

Abbreviations

BBPV: Benign paroxysmal positional vertigo

RMS: root mean square

HR: harmonic ratio

SVM: support vector machine model

DHI: Dizziness Handicap Inventory

ROC: receiver operating characteristic curve

AUC: Area under the curve

AP: anteroposterior

ML: mediolateral

VT: vertical

SR1: Step regularity

SR2: Stride regularity

Declarations

Ethics approval and consent to participate

The study was approved by the institutional human research ethics committee of School of Biomedical Engineering, Shanghai Jiao Tong University (protocol number:201807), and the trial was registered in the Chinese Clinical Trial Registry (ChiCTR1800015432) before the start of the study. All the participants provided written informed consent in accordance with the ethical guidelines.

Consent for publication

All the authors have approved the manuscript for publication.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The author(s) declare no potential conflicts of interest concerning this article.

Funding

This work was supported by the National Nature Science Foundation of China (Grant No. 11972233) and Key Technology Support Project of Shanghai Municipal Science and Technology Commission [Grant No. 16441908200 and 13441902900].

Author information

Affiliations

Shanghai Key Laboratory of Orthopaedic Implants, Department of Orthopaedic Surgery, Shanghai Ninth People's Hospital, Shanghai Jiao Tong University School of Medicine, Shanghai 200011, China

Yuqian Zhang & Dongyun Gu

School of Biomedical Engineering & Med-X Research Institute, Shanghai Jiao Tong University, Shanghai 200030, China

Yuqian Zhang, He Wang, Yifei Yao & Dongyun Gu

Engineering Research Center of Digital Medicine and Clinical Translation, Ministry of Education of People's Republic China. R. China, Shanghai 200030, China

Yuqian Zhang, He Wang, Yifei Yao & Dongyun Gu

Department of Neurological, Shanghai Ninth People's Hospital, Shanghai Jiao Tong University School of Medicine, Shanghai 200011, China;

Jianren Liu & Xuhong Sun

Authors' contributions

YZ: data acquisition and analysis, interpretation of the results, drafting and revision of the manuscript.

HW: data acquisition and analysis. YY: help in the study design and data analysis. JL: patient recruitment and study coordination. XS: study design, patient recruitment, statistical analysis, interpretation of the

results. DG: study design, interpretation of the results, revised the manuscript, funding acquisition and supervision of this study. All authors have read and approved the final manuscript.

Acknowledgments

The authors would like to thank Dr. Wei Chen, Dr. Jing Wu, and Dr. Liang Shu for assist in data collection, and Prof. Peter Bradley Shull for language editing.

References

1. Von Brevern M, Radtke A, Lezius F, Feldmann M, Ziese T, Lempert T, Neuhauser H (2007) Epidemiology of benign paroxysmal positional vertigo: a population based study. *Journal of Neurology, Neurosurgery & Psychiatry* 78 (7):710-715
2. Abbott J, Tomassen S, Lane L, Bishop K, Thomas N (2016) Assessment for benign paroxysmal positional vertigo in medical patients admitted with falls in a district general hospital. *Clinical Medicine* 16 (4):335
3. Helminski JO, Zee DS, Janssen I, Hain TC (2010) Effectiveness of particle repositioning maneuvers in the treatment of benign paroxysmal positional vertigo: a systematic review. *Physical therapy* 90 (5):663-678
4. Halker RB, Barrs DM, Wellik KE, Wingerchuk DM, Demaerschalk BM (2008) Establishing a diagnosis of benign paroxysmal positional vertigo through the dix-hallpike and side-lying maneuvers: a critically appraised topic. *The neurologist* 14 (3):201-204
5. Whitney SL, Marchetti GF, Morris LO (2005) Usefulness of the dizziness handicap inventory in the screening for benign paroxysmal positional vertigo. *Otology & Neurotology* 26 (5):1027-1033
6. Martellucci S, Pagliuca G, de Vincentiis M, Greco A, De Virgilio A, Nobili Benedetti FM, Gallipoli C, Rosato C, Clemenzi V, Gallo A (2016) Features of residual dizziness after canalith repositioning procedures for benign paroxysmal positional vertigo. *Otolaryngology–Head and Neck Surgery* 154 (4):693-701
7. Verdecchia DH, Monzón AM, Jaimes VU, da Silva Paiva L, Oliveira FR, de Carvalho TD (2020) Correlation between timed up and go, usual gait speed and dizziness handicap inventory in elderly with vestibular disorders: a retrospective and analytical study. *Archives of Physiotherapy* 10 (1):1-8
8. Chang W-C, Hsu L-C, Yang Y-R, Wang R-Y (2006) Balance ability in patients with benign paroxysmal positional vertigo. *Otolaryngology–Head and Neck Surgery* 135 (4):534-540
9. Çelebisoy N, Bayam E, Güleç F, Köse T, Akyürekli Ö (2009) Balance in posterior and horizontal canal type benign paroxysmal positional vertigo before and after canalith repositioning maneuvers. *Gait & posture* 29 (3):520-523
10. Kollén L, Frändin K, Möller M, Olsén MF, Möller C (2012) Benign paroxysmal positional vertigo is a common cause of dizziness and unsteadiness in a large population of 75-year-olds. *Aging clinical and experimental research* 24 (4):317-323

11. Kim SC, Kim JY, Lee HN, Lee HH, Kwon JH, beom Kim N, Kim MJ, Hwang JH, Han GC (2014) A quantitative analysis of gait patterns in vestibular neuritis patients using gyroscope sensor and a continuous walking protocol. *Journal of neuroengineering and rehabilitation* 11 (1):1-9
12. Angelini L, Hodgkinson W, Smith C, Dodd JM, Sharrack B, Mazzà C, Paling D (2020) Wearable sensors can reliably quantify gait alterations associated with disability in people with progressive multiple sclerosis in a clinical setting. *Journal of neurology*
13. Gaßner H, Jensen D, Marxreiter F, Kletsch A, Bohlen S, Schubert R, Muratori LM, Eskofier B, Klucken J, Winkler J (2020) Gait variability as digital biomarker of disease severity in Huntington's disease. *Journal of neurology*:1-8
14. Hubble RP, Naughton GA, Silburn PA, Cole MH (2015) Wearable sensor use for assessing standing balance and walking stability in people with Parkinson's disease: a systematic review. *PloS one* 10 (4):e0123705
15. Lança SM, Gazzola JM, Kasse CA, Branco-Barreiro FCA, Vaz DP, Scharlach RC (2013) Body balance in elderly patients, 12 months after treatment for BPPV. *Brazilian Journal of otorhinolaryngology* 79 (1):39-46
16. D'Silva LJ, Kluding PM, Whitney SL, Dai H, Santos M (2017) Postural sway in individuals with type 2 diabetes and concurrent benign paroxysmal positional vertigo. *International Journal of Neuroscience* 127 (12):1065-1073
17. Anson E, Pineault K, Bair W, Studenski S, Agrawal Y (2019) Reduced vestibular function is associated with longer, slower steps in healthy adults during normal speed walking. *Gait & posture* 68:340-345
18. Schniepp R, Möhwald K, Wuehr M (2019) Clinical and automated gait analysis in patients with vestibular, cerebellar, and functional gait disorders: perspectives and limitations. *Journal of neurology*:1-5
19. Schniepp R, Möhwald K, Wuehr M (2020) Key gait findings for diagnosing three syndromic categories of dynamic instability in patients with balance disorders. *Journal of neurology*
20. Bellanca J, Lowry K, VanSwearingen J, Brach J, Redfern M (2013) Harmonic ratios: a quantification of step to step symmetry. *Journal of biomechanics* 46 (4):828-831
21. Moe-Nilssen R, Helbostad JL (2004) Estimation of gait cycle characteristics by trunk accelerometry. *Journal of biomechanics* 37 (1):121-126
22. van Iersel MB, Rikkert MGO, Borm GF (2007) A method to standardize gait and balance variables for gait velocity. *Gait & posture* 26 (2):226-230
23. Weiss A, Sharifi S, Plotnik M, van Vugt JP, Giladi N, Hausdorff JM (2011) Toward automated, at-home assessment of mobility among patients with Parkinson disease, using a body-worn accelerometer. *Neurorehabilitation and neural repair* 25 (9):810-818
24. Ahmadi M, O'Neil M, Fragala-Pinkham M, Lennon N, Trost S (2018) Machine learning algorithms for activity recognition in ambulant children and adolescents with cerebral palsy. *Journal of NeuroEngineering and Rehabilitation* 15 (1):105. doi:10.1186/s12984-018-0456-x

25. Djordje Slijepcevic, Matthias Zeppelzauer, Anna-Maria Gorgas, Caterine Schwab, Michael Schuller, Arnold Baca, Christian Breiteneder, Horsak B (2018) Automatic Classification of Functional Gait Disorders. *IEEE J Biomed Health Inform* 22 (5):1653-1661
26. Di Girolamo S, Paludetti G, Briglia G, Cosenza A, Santarelli R, Di Nardo W (1998) Postural control in benign paroxysmal positional vertigo before and after recovery. *Acta oto-laryngologica* 118 (3):289-293
27. O'Connor SM, Kuo AD (2009) Direction-dependent control of balance during walking and standing. *Journal of neurophysiology* 102 (3):1411-1419
28. Brodie MA, Menz HB, Smith ST, Delbaere K, Lord SR (2015) Good lateral harmonic stability combined with adequate gait speed is required for low fall risk in older people. *Gerontology* 61 (1):69-78
29. Sekine M, Tamura T, Yoshida M, Suda Y, Kimura Y, Miyoshi H, Kijima Y, Higashi Y, Fujimoto T (2013) A gait abnormality measure based on root mean square of trunk acceleration. *Journal of neuroengineering and rehabilitation* 10 (1):1-7
30. Kunimune S, Okada S (2019) Contribution of vision and its age-related changes to postural stability in obstacle crossing during locomotion. *Gait & posture* 70:284-288
31. Brach JS, McGurl D, Wert D, VanSwearingen JM, Perera S, Cham R, Studenski S (2011) Validation of a measure of smoothness of walking. *Journals of Gerontology Series A: Biomedical Sciences and Medical Sciences* 66 (1):136-141
32. Menz HB, Lord SR, St George R, Fitzpatrick RC (2004) Walking stability and sensorimotor function in older people with diabetic peripheral neuropathy. *Archives of physical medicine and rehabilitation* 85 (2):245-252
33. Lowry KA, Smiley-Oyen AL, Carrel AJ, Kerr JP (2009) Walking stability using harmonic ratios in Parkinson's disease. *Movement disorders: official journal of the Movement Disorder Society* 24 (2):261-267
34. Doi T, Hirata S, Ono R, Tsutsumimoto K, Misu S, Ando H (2013) The harmonic ratio of trunk acceleration predicts falling among older people: results of a 1-year prospective study. *Journal of NeuroEngineering and Rehabilitation* 10 (1):7. doi:10.1186/1743-0003-10-7
35. Schniepp R, Schlick C, Schenkel F, Pradhan C, Jahn K, Brandt T, Wuehr M (2017) Clinical and neurophysiological risk factors for falls in patients with bilateral vestibulopathy. *Journal of neurology* 264 (2):277-283
36. Herman T, Mirelman A, Giladi N, Schweiger A, Hausdorff JM (2010) Executive control deficits as a prodrome to falls in healthy older adults: a prospective study linking thinking, walking, and falling. *Journals of Gerontology Series A: Biomedical Sciences and Medical Sciences* 65 (10):1086-1092
37. Mutlu B, Serbetcioglu B (2013) Discussion of the dizziness handicap inventory. *Journal of vestibular research* 23 (6):271-277
38. D'Silva LJ, Whitney SL, Santos M, Dai H, Kluding PM (2017) The impact of diabetes on mobility, balance, and recovery after repositioning maneuvers in individuals with benign paroxysmal positional vertigo. *Journal of diabetes and its complications* 31 (6):976-982

39. Martens C, Goplen FK, Aasen T, Nordfalk KF, Nordahl SHG (2019) Dizziness handicap and clinical characteristics of posterior and lateral canal BPPV. *European Archives of Oto-Rhino-Laryngology* 276 (8):2181-2189

Figures

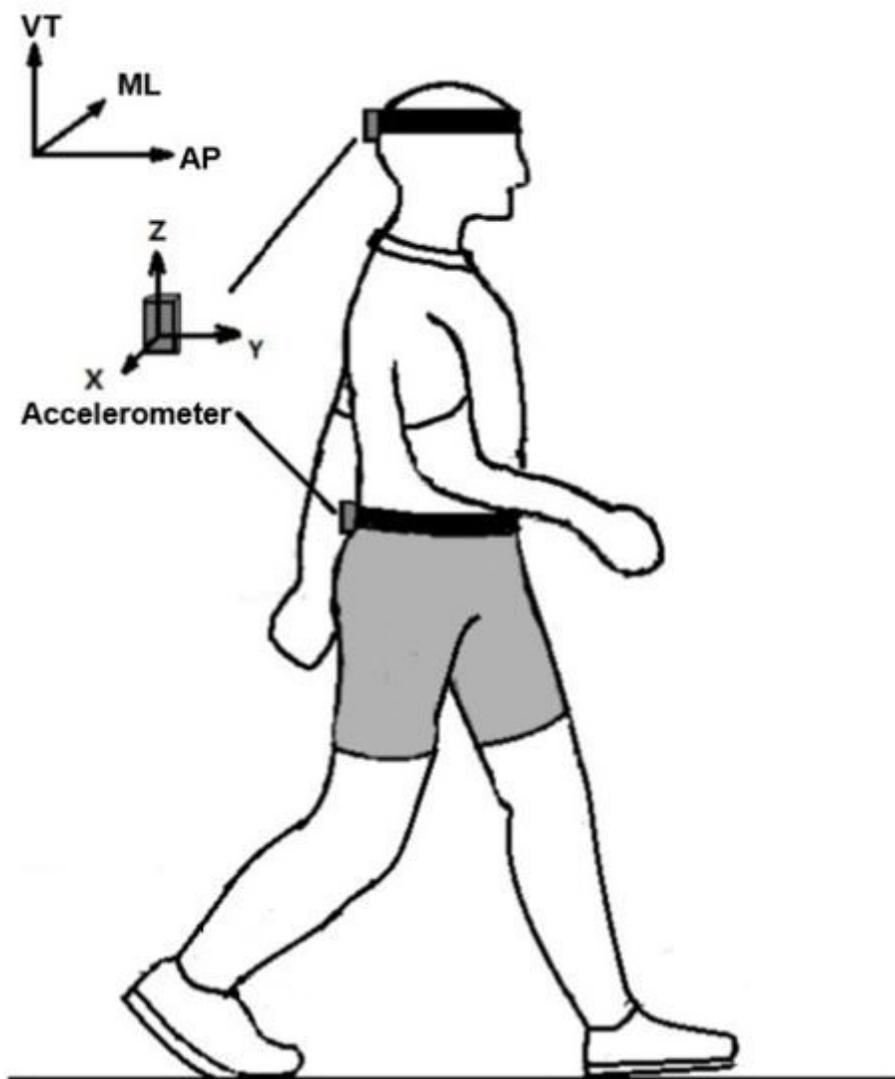


Figure 1

The accelerometers at the head and lower trunk were placed as the X-axis pointed to the right representing the mediolateral (ML) axis, the Y-axis pointed forwards representing the anteroposterior (AP) axis, and the Z-axis pointed to the upwards representing the vertical (VT) axis.

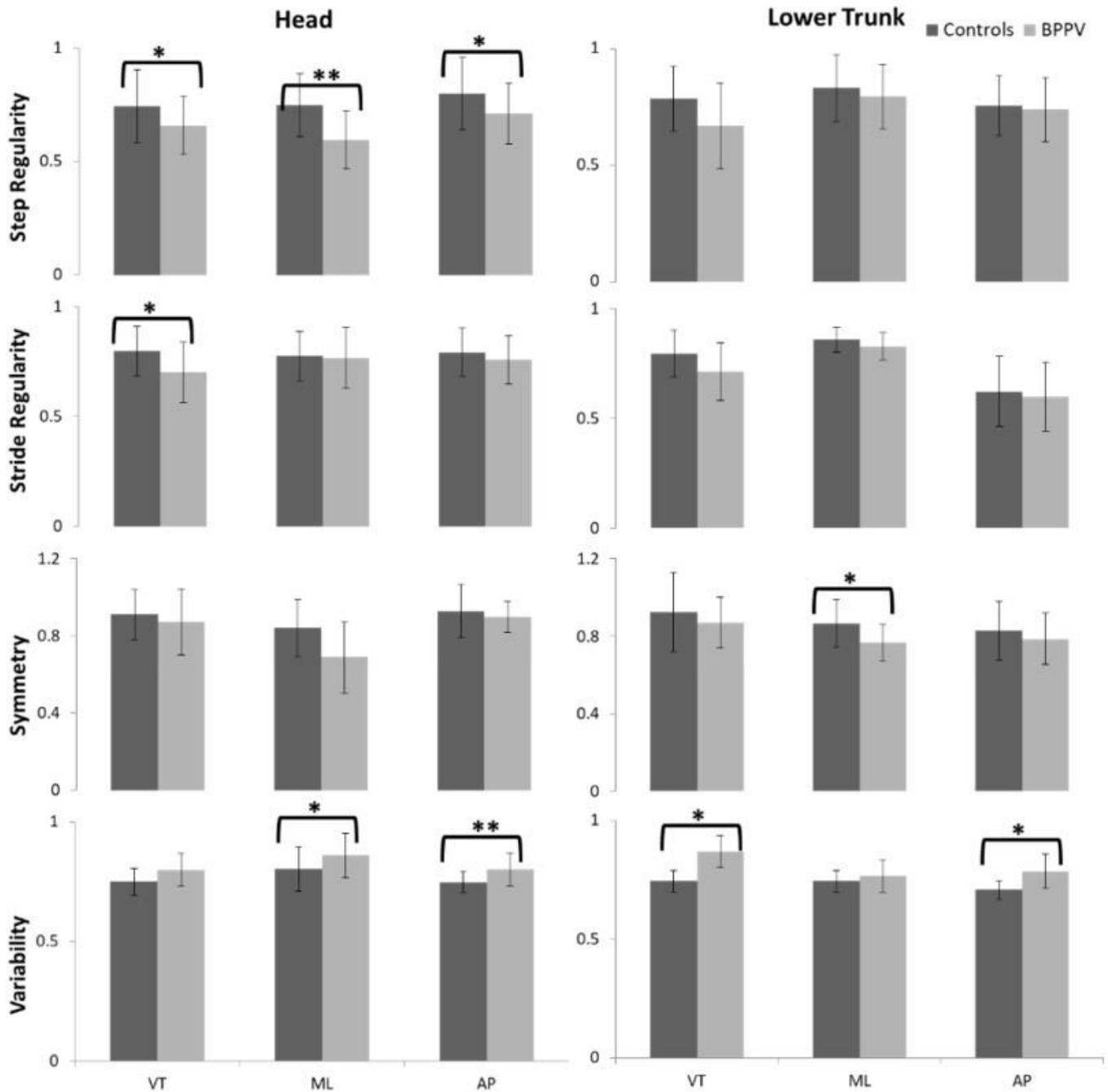


Figure 2

Differences in step regularity, stride regularity, gait symmetry and gait variability (* p < 0.05; ** p < 0.01). VT, ML, and AP refer to the vertical axis, mediolateral axis, and anteroposterior axis, respectively. Absolute value is adopted.

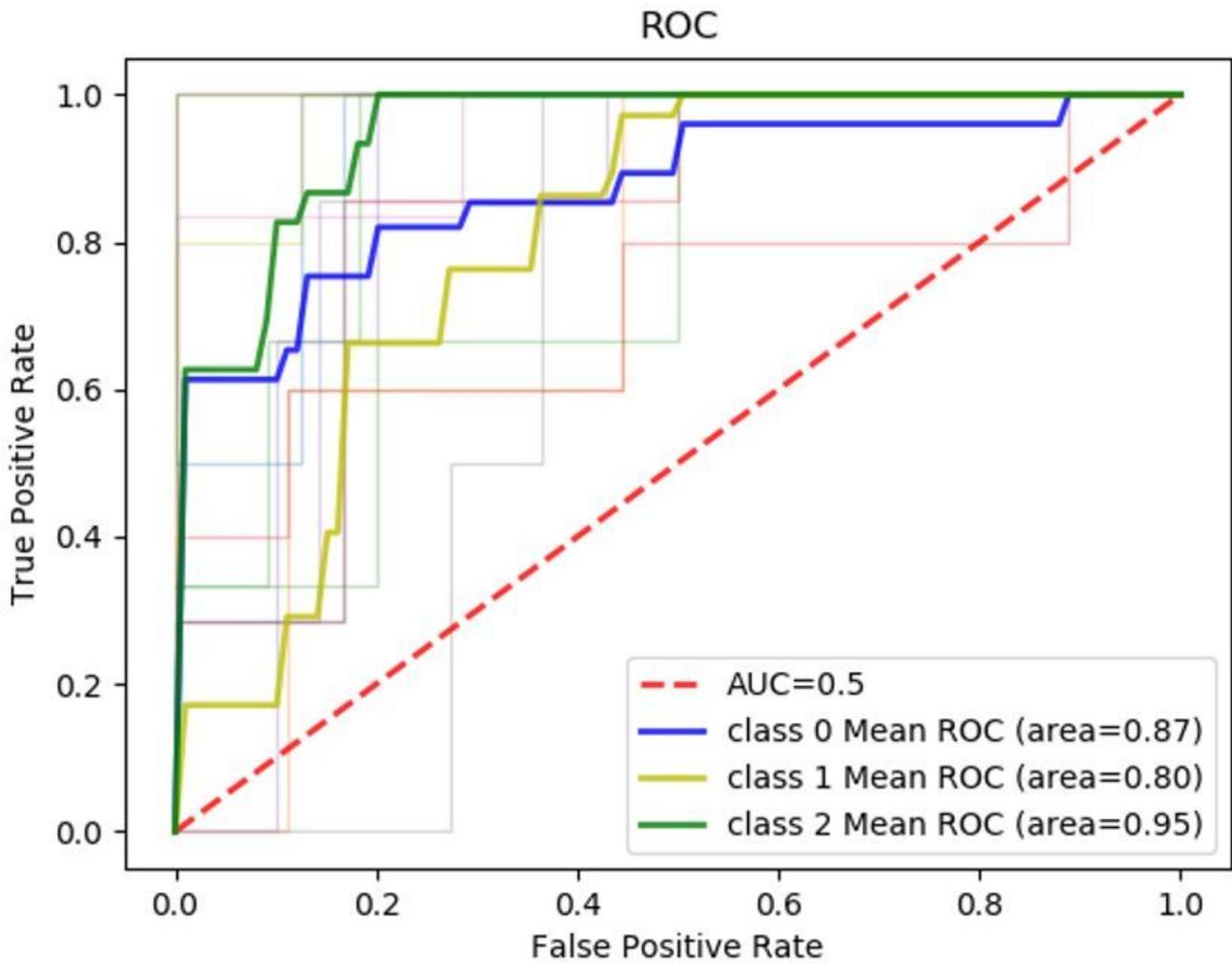


Figure 3

ROC and AUC for DHI subgroups classification of BPPV disease. Class 0: mild stage, class 1: moderate stage, class 2: severe stage.