Instrumental assessment of dynamic postural stability in patients with unilateral vestibular hypofunction during straight, curved, and blindfolded gait

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Abstract

Purpose

To characterise dynamic postural stability of gait in patients with vestibular hypofunction (PwVH) using a sensor-based assessment while performing dynamic tasks and to correlate the results of this evaluation with clinical scales.

Methods

This cross-sectional study involved 22 adults between 18–70 years old from a healthcare hospital centre. Eleven patients suffering from chronic vestibular hypofunction (PwVH) and eleven healthy controls (HC) were evaluated through a combined inertial sensor-based and clinical scale assessment. Participants were equipped with five synchronised inertial measurement units (IMUs) (128Hz, Opal, APDM, Portland, OR, USA): three IMUs were located on the occipital cranium bone, near the lambdoid suture of the head, at the centre of the sternum, and at L4/L5 level, just above the pelvis, and were used to quantify gait quality parameters, while the other two were located slightly above lateral malleoli and used to perform stride and step segmentation. Three different motor tasks were performed in a randomized order: the 10-meter Walk Test (10MWT), the Figure of Eight Walk Test (F8WT) and the Fukuda Stepping Test (FST). A set of gait quality parameters related to stability, symmetry and smoothness of gait were extracted from IMU data and correlated with the clinical scale scores. PwVH and HC results were compared to test for significant between-group differences.

Results

Significant differences were found for the three motor tasks (10MWT, F8WT and FST) when comparing PwVH and HC groups. For the 10MWT and the Fo8WT, significant differences between the PwVH and HC groups were found for the stability indexes. Considering the FST, significant differences between the PwVH and HC groups were also found in the stability and symmetry of gait. A significant correlation was found between the Dizziness Handicap Inventory and gait indices during the F8WT.

Conclusions

In this study, we characterized the dynamic postural stability alterations during linear, curved, and blindfolded walking/stepping in PwVH combining an instrumental IMU-based with traditional clinical scales approach. Combining instrumental and clinical evaluation for dynamic stability of gait alterations in PwVH is useful in thoroughly evaluating the effects of unilateral vestibular hypofunction.

1. Introduction

Postural stability is a multifactorial ability in which proprioceptive, visual, vestibular, and cognitive systems interact [1]. To ensure posture regulation in both static and dynamic situations, the central nervous system combines the information coming from these systems into a constant sensory reweighting [2]. Each sensory system's contribution differs based on the surroundings and the motor task that the individual is performing [1,3–5].

Vestibular hypofunction (VH) can cause dizziness, vertigo, and postural instability, as well as sensations of falling while standing or walking, due to decreased function of the affected ear, which results in ipsilateral vestibulo-spinal responses. Indeed, VH restricts the amplitude and velocity of head movement during dynamic tasks such as those usually performed during daily activities (i.e., walking to reach a place). Furthermore, patients with VH (PwVH) have reported difficulties in walking in the dark or while performing a cognitive-motor dual-task (DT), defined as the simultaneous performance of two tasks [6]. Several studies have also shown how the vestibular information influences gait performance, inducing changes in the percentage of double stance phase as well as in the head and trunk stability of patients with unilateral/bilateral vestibular loss [7–12].

Nowadays, new otoneurologic tests are available to measure all vestibular receptor functions in the different stages of VH. These tests allow for a dynamic evaluation of the Vestibulo Ocular Reflex (VOR) and the vestibular nerve functions. Indeed, using the cervical and ocular vestibular evoked myogenic potentials (VEMPs) and the video head impulse test (vHIT), it is possible to study the functioning of both the otolith and semicircular canals.

Motor ability assessment is of utmost importance in this class of patients. While this is typically performed using clinical scales, promising results were obtained using instrumental assessments of gait stability, showing that PwVH have difficulty in walking with a straight trajectory when turning their head [11], and this difficulty is even more evident while walking in the dark. In a recent study, head and trunk linear accelerations were evaluated during locomotion in PwVH [13] and it was found that head and trunk control was significantly impaired in PwVH when compared with healthy participants during vision-absent conditions. This evidence lay the foundations for adopting objective and instrumented evaluations, able to quantify gait and postural impairments in PwVH as already performed in the last few years in patients with neurological disorders [14]. Furthermore, to quantify postural impairments in different conditions could help the clinician in better designing the rehabilitation programmes [15] and to evaluate their effectiveness [16]. Current developments in body-worn inertial sensors promise a more accurate and detailed evaluation of gait alterations than an assessment based

only with clinical scales, that is still subjective and not sensitive enough to identify postural stability dysfunctions. Indeed, from inertial measurement units (IMUs), specific information can be obtained on fundamental aspects of gait quality. Based on trunk acceleration and velocity patterns during locomotion, IMUs-based assessment can accurately quantify dynamic trunk behaviour [17] and gait characteristics [18]. Gait quality indexes have been proposed to characterize the severity of gait alteration and the risk of falls in patients with neurological disorders [19]. Furthermore, by combining the derived measures of IMUs placed in distinct regions of the body it is possible to synchronize changes in trunk mechanics and measure the gait smoothness [20,21]. It appears therefore critical to explore the effect of VH on the gait quality indexes and examine the differences during distinct dynamic motor tasks. Compromised postural control has been already demonstrated in PwVH during straight walking [22] but in everyday life, curved trajectories are commonly faced, and represent a challenge for people with gait disorders [23], even more in blindfolded gait, which are considered very challenging for people with vestibular impairments [24,25]. Unfortunately, curved and/or blindfolded paths have rarely been considered so far [11,23,25,26].

For these reasons our primary hypothesis wasthat dynamic postural stability characteristics could be different during linear, curved, and blindfolded pathways in PwVH. In addition, we hypothesized that the instrumental measures can be correlated with clinical scale scores. As a result, the aim of this study is to characterise postural and gait in PwVH using a sensor-based assessment while performing dynamic tasks and to correlate the results of this evaluation with clinical scales.

2. Materials and Methods

This cross-sectional study was carried out at the IRCCS Santa Lucia Foundation, and it was approved by the Local Independent Ethics Committee of Fondazione Santa Lucia IRCCS (protocol number: ProtCE/2022_011). All procedures contributing to this work comply with the ethical standards of the relevant national and institutional guidelines on human experimentation and with the World Medical Association Declaration of Helsinki. All participants gave written consent to publish the results obtained from their clinical examinations and instrumental tests.

2.1 Participants

Two groups of 22 participants were involved based on consecutive sampling. This sample size met the minimum requirement set by an a priori power analysis for nonparametric within and between-group

comparisons conducted on previous studies ($\alpha = 0.05$; $\beta = 0.8$; ES = 0.6) [11,12]. The first group was composed of 11 patients suffering from VH (PwVH, age: 54.91±8.65 years, 8 females). PwVH were eligible if they were aged between 18–70 years, had disturbances in static and dynamic balance, had an impact on the activities of daily living (ADLs) evaluated with the dizziness handicap inventory (DHI) and a diagnosis of vestibular hypofunction performed with a medical bedside examination and instrumental assessment with video head impulse test (vHIT). Participants with bilateral hypofunction, neurological, orthopaedic, and/or other medical conditions that would interfere in the study procedures were excluded. The second group was composed of 11 healthy adults control (HC) without neurological, orthopaedic and/or vestibular pathology (HC, age: 56.45±11.21 years, 7 females). The two groups' demographic characteristics and clinical scale scores are reported in Table 1.

Table 1

Demographic characteristics of the two groups and clinical scale scores. Mean and standard deviation values are displayed.

	PwVH	**HC**
Nr. of Participants	11	11
Sex	8 females	7 females
Age (years)	54.91 ± 8.65	56.45 ± 11.21
BBS	54.82 ± 1.78	NA
DHI	73.27 ± 7.17	NA
Diagnosis	Vestibular neuritis (7) Ménière Disease (3) Vestibular neurectomy (1)	NA

PwVH= patients with vestibular hypofunction; HC = healthy control group; BBS = Berg Balance Scale; DHI = Dizziness Handicap Inventory, NA = Not Applicable.

2.2 Instrumentation and experimental protocol

During the procedure for data acquisition, participants were instructed to perform three different motor tasks (Fig.1). First, participants were asked to stand still for 5 s and to perform a 10-Meter Walk Test (10MWT) (Fig.1-a), for three times consecutively, on a 14 meter-straight pathway at their self-selected walking speed; the first and the last 2 meters represent the acceleration and deceleration times before and after the 10 meters (green line Fig 1-a). Subsequently, participants were asked to perform the Figure-of-8 Walk Test (Fo8WT) (Fig.1-b), twice per each side (right and left) [23] and finally, the Fukuda Stepping Test (FST) (Fig.1-c) [23,24]. Furthermore, for each patient, static and dynamic balance, ambulation skills, and mobility deficits were assessed through the Berg Balance Scale (BBS)[26] by an

expert physiotherapist blinded to the instrumental assessment. The BBS is used to objectively determine a patient's ability (or inability) to safely balance during a series of predetermined tasks. It is a 14 item list with each item consisting of a five-point ordinal scale ranging from 0 to 4, with 0 indicating the lowest level of function and 4 the highest level.

As above mentioned, the perceived handicap related to dizziness was also evaluated using the the DHI, a self-assessment inventory, including 25 questions to

a)

b)

c)

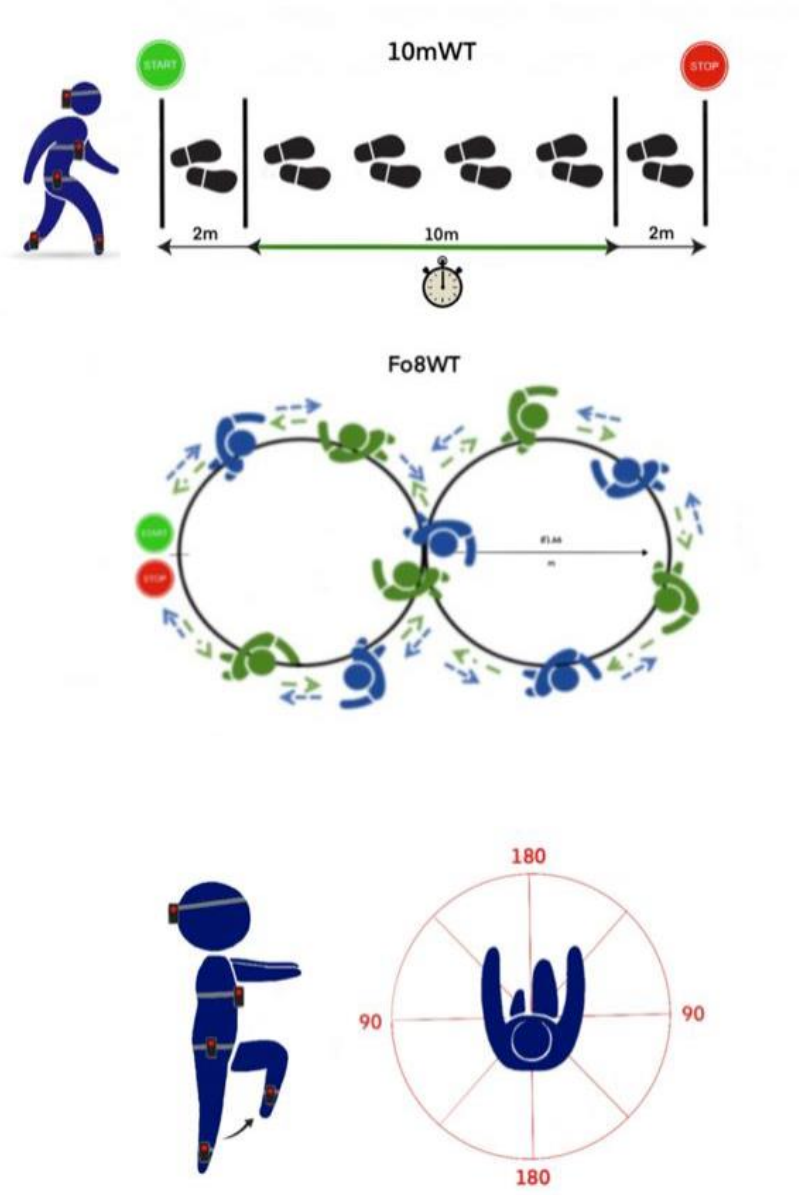

Figure 1 Illustration on the 3 tests performed.

Figure (a): schematic representation of the 10MWT, patients were asked to walk at their preferred speed on a 14 m trail; Figure (b): F8WT, Clockwise and counter-clockwise directions are indicated

with blue and green arrows, respectively; Figure (c): FST, patients were asked to walk on the spot with eyes closed and arms in front of them.

evaluate self-perceived activity limitation and restriction resulting from dizziness [27]. The function of the semicircular canals was measured using vHIT (OtosuiteV®, GN Otometrics, Denmark) during HIMP. The criterion for a normal VOR velocity gain was that it should be 0.68 or greater, based on HIT data from previously published trials in which the mean HIT velocity gain measured by search coils with identical apparatus and procedures to those used here was 0.81 0.068 standard deviations so that the mean 2 standard deviations units incorporates 95% of the population and yields a lower cutoff of 0.68. Gain value <0.76 identify the affected side of unilateral VH [28].

2.3 Gait quality instrumental assessment

During the performance of each task (10MWT, F8WT and FST), participants were equipped with five synchronised IMUs (128Hz, Opal, APDM, Portland, OR, USA), measuring three-dimensional linear accelerations and angular velocities. IMUs were located on the occipital cranium bone, near the lambdoid suture of the head (H), at the centre of the sternum (S), and the L4/L5 level, just above the pelvis (P). For step and stride segmentation, one IMU was placed on each shank, just above the lateral malleoli. All IMUs were attached to the participant's body with Velcro straps, except the IMU on the head, which was in a specially designed compartment of a swim cap. The data were processed in MATLAB® environment (MATLAB R2021b, MathWorks) for the extraction of spatiotemporal and gait quality parameters. The following spatiotemporal parameters and gait quality indices were obtained for the three tasks:

- Spatiotemporal:

- For the gait tasks: (i) Average walking speed (WS) as the ratio between total distance and time to complete the test; (ii) average stride duration (ASD) as the ratio between time to complete the test and the number of strides; (iii) average stride frequency (SF) as the total number of strides divided by the time needed to complete the test. The number of strides was automatically obtained through a peak detection algorithm on the Medio-Lateral (ML) angular velocity signals measured by the two IMUs on the shanks [15,16].
- Instead, for the FST, the number of steps (Nr_{step}), step frequency ($Freq_{step}$) and step duration (AD_{step}) were taken into consideration.

- Stability:
  - Normalized Root Mean Square (nRMS) of the acceleration measured at pelvis, trunk, and head levels. The RMS values of each stride acceleration were obtained for the Antero-Posterior (AP), ML, and Cranio-Caudal (CC) components. To take the influence of the walking speed into account, the AP and ML components were then divided by the CC component, as suggested by [29]. High nRMS values have been associated with higher levels of acceleration, and hence, decreased stability [23]:

$$RMS_jK = \frac{1}{N}\sqrt{\sum_{i=1}^{N} a_i^2} \quad ; \quad nRMS_jK = \frac{RMS_jK}{RMS_{CC}K}$$

    where j is the component (AP and ML), K represents the upper body level (Pelvis, Sternum, Head), N is the number of sample data, and a is the acceleration signal.
  - Attenuation coefficients (AC) [16] between each level pair of the upper-body (pelvis-sternum, pelvis-head, sternum-head), for each acceleration component (AP, ML and CC) defined as:

$$ACPS_j = \left(1 - \frac{RMS_{S_j}}{RMS_{P_j}}\right) * 100$$
$$ACPH_j = \left(1 - \frac{RMS_{H_j}}{RMS_{P_j}}\right) * 100$$
$$ACSH_j = \left(1 - \frac{RMS_{H_j}}{RMS_{S_j}}\right) * 100$$

    where j represents the direction AP, ML and CC.

    Each coefficient represents the variation of the acceleration from lower to upper-body levels. A positive coefficient indicates an attenuation of the accelerations, while a negative coefficient indicates an amplification of the accelerations from the lower to the upper body level. It has been demonstrated that, in typical walking, accelerations are attenuated from the pelvis to the head to stabilise the optic flow and increase the head stability [30].

- Symmetry: improved Harmonic Ratio (iHR) [18] measured at the level of the pelvis, for each acceleration component (AP, ML and CC). This parameter ranges from 0% (total asymmetry) to 100% (total symmetry). It is calculated as:

$$iHR_j = \frac{\sum power\ of\ intrinsic\ harmonics}{\sum power\ of\ intrinsic\ harmonics + \sum power\ of\ extrinsic\ harmonics} \cdot 100$$

  where j represents the direction AP, ML and CC.

- Smoothness: log dimensionless jerk (LDLJ) measured at the pelvis level, calculated from the linear acceleration and angular velocity signals, LDLJa and LDLJv, respectively.
  With reference to LDLJ(v), it is defined as [21]:

$$LDLJ(\boldsymbol{v}) \triangleq -\ln\left(\frac{(t_2 - t_1)^3}{v_{peak}^2}\int_{t_1}^{t_2}\left\|\frac{d^2}{dt^2}\boldsymbol{v}(t)\right\|_2^2 dt\right);$$
$$v_{peak} \triangleq \max_{t\in[t_1,t_2]}\left\|\boldsymbol{v}(t)\right\|_2$$

  where **v**(t) represents the angular velocity of the movement in the time domain; t_1 and t_2 represent the beginning and end of the movement, respectively. Lower LDLJ values have been associated with a higher level of smoothness of a translational/rotational movement.

2.4 Statistical analysis

Descriptive and inferential statistical analysis was performed using the IBM SPSS Statistics software (v23, IBM Corp., Armonk, NY, U.S.A.). Statistical level of significance was set at alpha = 0.05. The normal distribution of each parameter was verified using the Shapiro-Wilk test. As most of the parameters were not normally distributed, non-parametric tests were performed. To investigate if significant differences existed between the two groups, the Mann-Whitney U test was used on all estimated parameters. A Spearman's rank correlation coefficient (ρ) was used to assess the relationship between gait quality indices and clinical scale scores.

3 Results

Significant differences were found for the three motor tasks (10mWT, F8WT and FST) when comparing PwVH and HC groups.

For the 10MWT, the Mann-Whitney U test revealed significant differences between the PwVH and HC groups in the ML axis for both nRMS at pelvis (U = 17.00, z = -2.86, p = 0.003) and AC from pelvis to sternum level (U = 29.00, z = -2.07, p = 0.040). Also, the iHR in the AP (U =22.00, z = -2.53, p = 0.010) and CC axis (U = 23.00, z = -2.46, p = 0.013) were found significantly different between the groups.

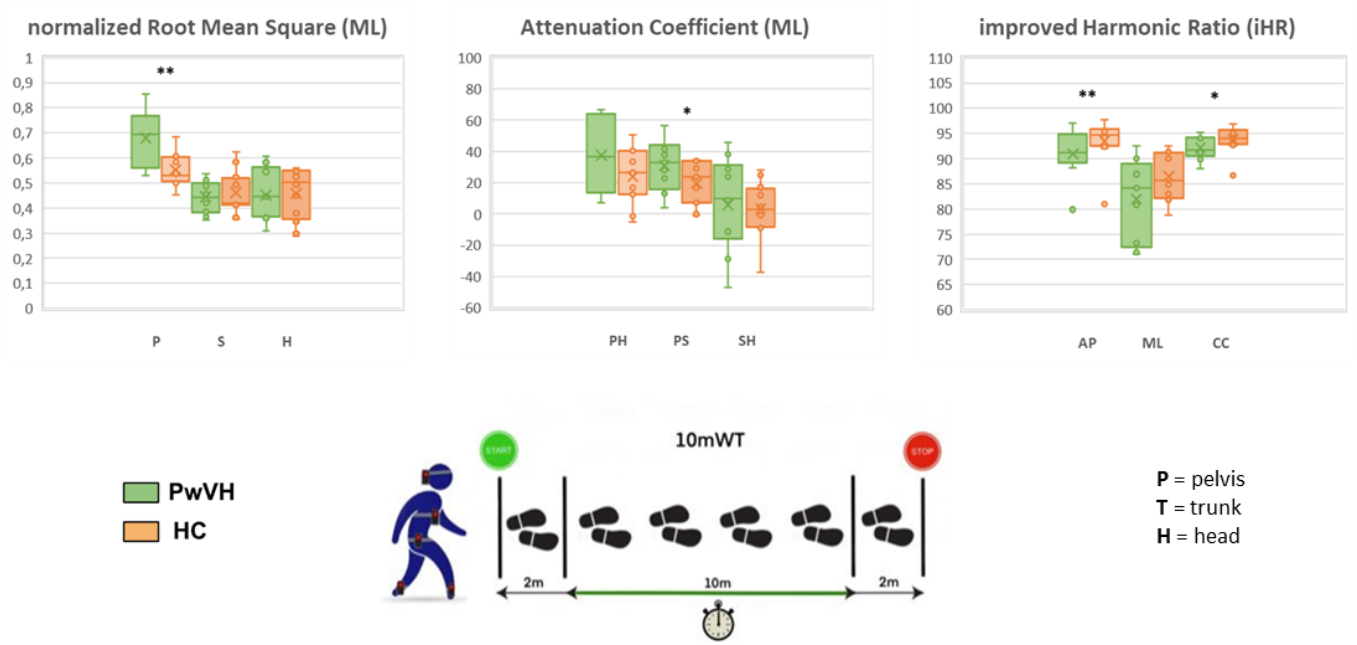

Figure 2. Normalized root mean square (nRMS) values, attenuation coefficients (AC) and improved harmonic ratio (iHR) for the PwVH and HC groups during 10mWT at time T0. Medians and interquartile ranges are reported. AP, antero-posterior; ML, medio-lateral; CC, cranio-caudal; P, pelvis; S, sternum; H, head. The asterisks indicate statistically significant between-groups differences (* p < 0,05; ** p < 0,001).

Considering the Fo8WT, significant differences between the PwVH and HC groups were also found in the ML axis for the nRMS at pelvis level (U = 26.00, z = -2.27, p = 0.023), for the AC from pelvis to head level (U = 9.00, z = -3.38, p = 0.001), and AC from sternum to head level (U=30, z=-2.00, p = 0.047). Also, the iHR in the CC axis (U = 25.00, z = -2.33, p = 0.019) was found significantly different between the two groups.

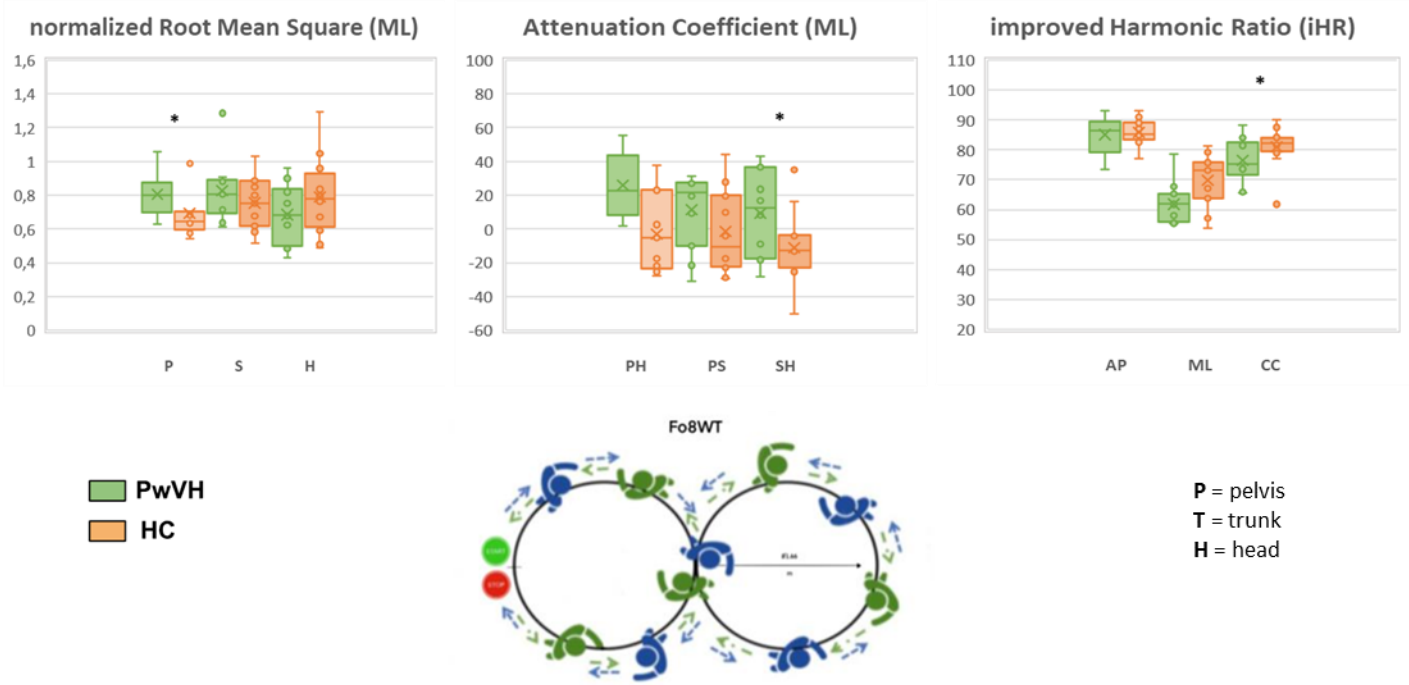

Figure 3. Normalized root mean square (nRMS) values, attenuation coefficients (AC) and improved harmonic ratio (iHR) for the PwVH and HC groups during F8WT at time T0. Medians and interquartile ranges are reported. AP, antero-posterior; ML, medio-lateral; CC, cranio-caudal; P, pelvis; S, sternum; H, head. The asterisks indicate statistically significant between-groups differences (* $p < 0,05$; ** $p < 0,001$).

For the FST, the Mann-Whitney U test revealed a significant difference for the iHR in the ML axis between the PwVH and HC groups ($U = 20.00$, $z = -2.66$, $p = 0.007$).

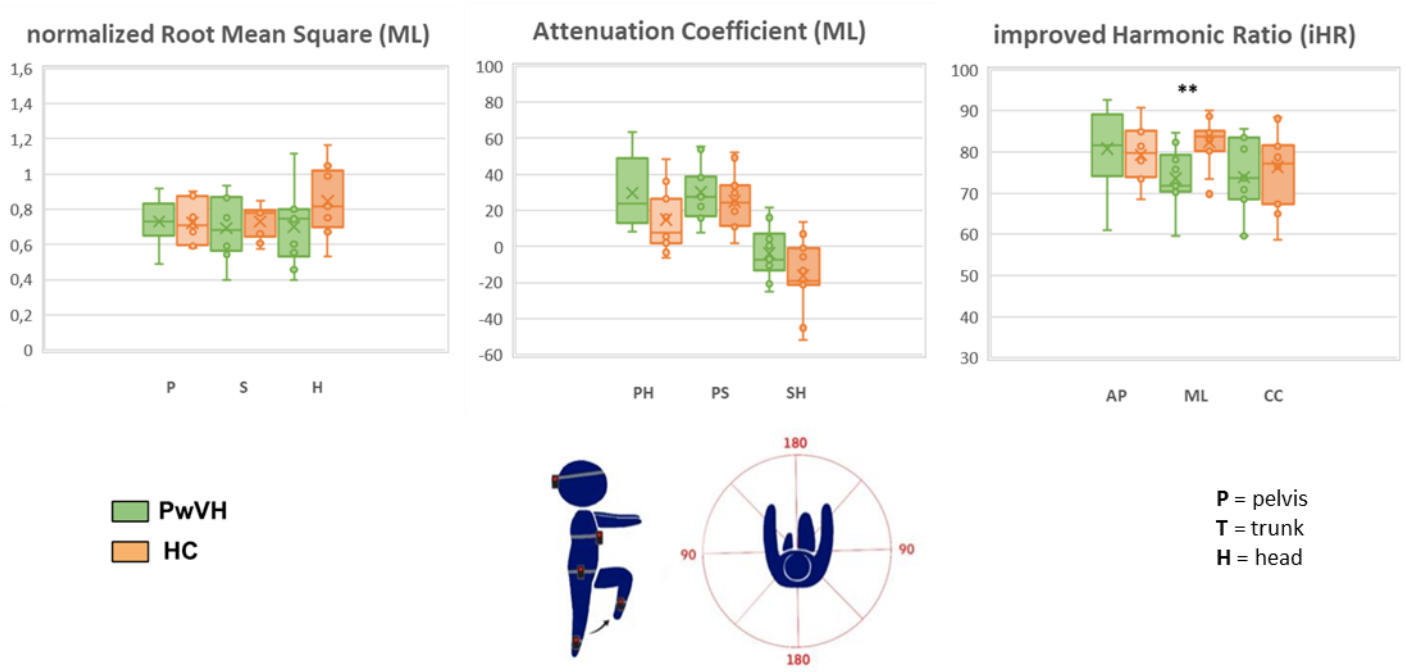

Figure 4. Normalized root mean square (nRMS) values, attenuation coefficients (AC) and improved harmonic ratio (iHR) for the PwVH and HC groups during FST at time T0. Medians and interquartile ranges are reported. AP, antero-posterior; ML, medio-lateral; CC, cranio-caudal; P, pelvis; S, sternum; H, head. The asterisks indicate statistically significant between-groups differences (* $p < 0,05$; ** $p < 0,001$).

Spatiotemporal and gait quality parameters from all motor tasks are reported in table 2.

Table 2 Medians and interquartile ranges (in square brackets) of spatiotemporal and gait quality parameters for the two groups (PwVH and HC).

Spatiotemporal				
Parameter	Group	10MWT	Fo8WT	FST
WS [$m \cdot s^{-1}$]	PwVH	1.05 [0.38]	0.86 [0.27]	-
	HC	1.15 [0.17]	0.78 [0.20]	-
AD_{stride} [s]	PwVH	1.34 [0.27]	1.52 [0.24]	-
	HC	1.26 [0.18]	1.67 [0.45]	-
$Freq_{stride}$ [$stride \cdot s^{-1}$]	PwVH	0.74 [0.15]	0.66 [0.10]	-
	HC	0.80 [0.11]	0.60 [0.18]	-
Nr_{step} [dimless]	PwVH	-	-	100 [26]
	HC	-	-	94 [18]
AD_{step} [s]	PwVH	-	-	0.63 [0.13]
	HC	-	-	0.64 [0.17]
$Freq_{step}$[$step \cdot s^{-1}$]	PwVH	-	-	1.60 [0.31]
	HC	-	-	1.57 [0.39]

Gait quality indices					
Parameter		Group	10MWT	Fo8WT	FST
nRMS P	AP	PwVH	0.77 [0.42]	0.88 [0.22]	0.78 [0.38]
		HC	0.73 [0.08]	0.86 [0.10]	0.67 [0.39]
	ML	PwVH	0.70 [0.24]**	0.81 [0.20]*	0.71 [0.34]
		HC	0.52 [0.10]**	0.65 [0.11]*	0.71 [0.28]
nRMS S	AP	PwVH	0.43 [0.16]	0.53 [0.12]	0.62 [0.25]
		HC	0.48 [0.18]	0.61 [0.13]	0.65 [0.27]
	ML	PwVH	0.46 [0.13]	0.81 [0.25]	0.62 [0.32]
		HC	0.49 [0.10]	0.75 [0.27]	0.78 [0.19]
nRMS H	AP	PwVH	0.33 [0.19]	0.48 [0.41]	0.49 [0.27]
		HC	0.37 [0.13]	0.61 [0.23]	0.51 [0.35]
	ML	PwVH	0.38 [0.24]	0.68 [0.33]	0.74 [0.34]
		HC	0.51 [0.20]	0.81 [0.26]	0.76 [0.32]
AC PH	AP	PwVH	54.11 [33.22]	43.09 [38.88]	61.78 [19.29]
		HC	56.57 [13.83]	29.87 [23.84]	42.58 [17.25]
	ML	PwVH	45.21 [48.96]	27.08 [45.23]***	24.74 [35.94]
		HC	16.98 [42.10]	-17.46 [27.89]***	7.85 [34.25]
	CC	PwVH	5.71 [20.25]	3.31 [16.75]	30.21 [26.63]

		HC	8.85 [8.98]	5.89 [16.63]	28.04 [16.86]
AC PS	AP	PwVH	47.49 [21.14]	35.24 [20.72]	41.70 [28.54]
		HC	40.09 [24.35]	31.23 [15.04]	45.71 [50.70]
	ML	PwVH	32.81 [28.15]*	21.55 [37.30]	27.66 [22.09]
		HC	16.83 [29.15]*	-4.06 [39.59]	24.25 [22.19]
	CC	PwVH	-3.25 [28.26]	5.44 [28.02]	24.62 [25.19]
		HC	5.11 [11.59]	6.02 [8.53]	27.03 [20.10]
AC SH	AP	PwVH	9.48 [58.45]	-1.37 [47.23]	21.70 [28.91]
		HC	32.34 [26.98]	-6.05 [32.85]	26.89 [49.20]
	ML	PwVH	10.57 [49.51]	16.91 [53.73]*	-7.05 [26.61]
		HC	4.41 [25.71]	-12.10 [19.57]*	-13.55 [27.14]
	CC	PwVH	-1.11 [12.11]	-5.50 [12.13]	-0.19 [17.10]
		HC	4.52 [4.40]	0.82 [11.51]	2.41 [12.12]
iHR	AP	PwVH	90.76 [6.55]**	86.37 [10.50]	81.65 [15.01]
		HC	95.34 [3.03]**	87.00 [7.09]	77.96 [12.50]
	ML	PwVH	80.77 [16.86]	61.85 [9.29]	71.51 [7.95]**
		HC	85.84 [9.56]	73.35 [18.59]	83.69 [4.83]**
	CC	PwVH	91.58 [6.23]*	74.89 [16.23]*	73.66 [15.07]
		HC	94.23 [2.39]*	82.57 [3.78]*	77.16 [14.01]
LDLJa	AP	PwVH	-4.98 [0.31]	-	-5.25 [0.38]
		HC	-5.15 [0.46]	-	-5.19 [0.24]
	ML	PwVH	-5.48 [0.42]	-	-5.53 [0.43]
		HC	-5.50 [0.23]	-	-5.52 [0.38]
	CC	PwVH	-5-03 [0.56]	-	-5.63 [0.34]
		HC	-5.06 [0.36]	-	-5.61 [0.29]
LDLJv	AP	PwVH	-	-4.14 [0.33]	-4.23 [0.76]
		HC	-	-4.37 [0.72]	-4.64 [0.59]
	ML	PwVH	-	-3.92 [0.74]	-4.62 [0.63]
		HC	-	-4.08 [0.46]	-4.67 [0.34]
	CC	PwVH	-	-3.43 [0.34]	-3.99 [0.71]
		HC	-	-3.42 [0.36]	-3.63 [0.58]

Abbreviations: WS= walking speed; AD_{stride}= average stride duration; $Freq_{stride}$, stride frequency; Nr_{step}, number of steps; AD_{step}, step duration; $Freq_{step}$, step frequency; nRMS, normalized root mean squared; AC, attenuation coefficient; iHR, improved harmonic ratio; LDLJa, log dimensionless jerk from linear acceleration; LDLJv, log dimensionless jerk from angular velocity; AP, antero-posterior; ML, medio-lateral; CC, cranio-caudal; P, pelvis; S, sternum; H, head. Significant levels: * $p<0.05$, ** $p<0.01$, *** $p< 0.001$.

Results about the correlation analysis between IMU-based parameters and clinical scores are reported in table 3. During the 10MWT several correlations exist among the DHI clinical scale and gait stability (nRMS_H_AP and nRMS_H_ML, ACPH_AP and ACPH_ML, ACSH_ML and ACSH_CC) and smoothness (LDLJa_ML) parameters. During the F8WT the nRMS_H_ML positively correlated with BBS scale and negatively with the DHI scale, while during the FST a negative correlation has been found between DHI scale and nRMS_S_ML, and positive correlations between BBS scale and ACPH_CC and BBS scale and LDLJv_CC.

Table 3 Spearman's correlation coefficients (ρ) between instrumental evaluation and clinical scales for the three motor tasks. Significant correlations are indicated by asterisks (*$p < 0.05$; **$p < 0.01$).

Spatiotemporal	**10MWT**		**Fo8WT**		**FST**	
Parameter	BBS	DHI	BBS	DHI	BBS	DHI
WS [m·s-1]	.275	.199	.095	-.171	-	-
AD_{stride} [s]	.528	.065	.518	.083	-	-
$Freq_{stride}$ [stride·s-1]	-.528	-.065	-.518	-.083	-	-
Nr_{step} [dimless]	-	-	-	-	-.306	-.388
AD_{step} [s]	-	-	-	-	.395	.299
$Freq_{step}$[step·s-1]	-	-	-	-	.306	.388

Gait quality indices		10MWT		Fo8WT		FST	
Parameter		BBS	DHI	BBS	DHI	BBS	DHI
nRMS P	AP	-.391	.194	-.275	.342	-.079	-.254
	ML	-.084	.457	.449	.102	-.354	-.365
nRMS S	AP	.385	-.042	.422	-.296	-.153	-.240
	ML	.401	-.370	.217	-.434	.206	-.647*
nRMS H	AP	.137	-.670*	.164	-.411	-.111	-.328
	ML	.454	-.739**	.613*	-.702*	.106	-.420
AC PH	AP	-.164	.661*	-.121	.513	.306	.416
	ML	-.158	.716*	-.121	.739**	-.095	.351
	CC	.470	-.092	.512	-.115	.787**	.088
AC PS	AP	-.306	.152	-.364	.120	.264	.037
	ML	-.153	.402	.132	.397	-.206	.125
	CC	.296	-.208	-.016	-.226	.597	-.199
AC SH	AP	.185	.540	-.180	.471	.048	.517
	ML	-.222	.698*	-.438	.591	-.100	.296
	CC	-.317	.605*	.238	.217	.048	.434
iHR	AP	-.238	.323	-.459	.009	.201	-.176
	ML	.069	.106	.032	.222	.211	-.531
	CC	.375	-.222	.063	-.337	.438	-.217
LDLJa	AP	-.502	.314	-	-	-.243	-.092
	ML	.090	.614*	-	-	-.063	.129
	CC	-.565	.028	-	-	.106	.102
LDLJv	AP	-	-	-.195	.083	.364	.319
	ML	-	-	.354	-.504	-.084	-.240
	CC	-	-	-.438	.129	.681*	-.397

Abbreviations: BBS, Berg Balance Scale; DHI, Dizziness Handicap Inventory; WS, walking speed; AD_{stride}, average stride duration; $Freq_{stride}$, stride frequency; Nr_{step}, number of steps; AD_{step}, step duration; $Freq_{step}$, step frequency; nRMS, normalized root mean squared; AC, attenuation coefficient; iHR, improved harmonic ratio; LDLJa, log dimensionless jerk from the linear acceleration; LDLJv, log dimensionless jerk from angular velocity; AP, antero-posterior; ML, medio-lateral; CC, cranio-caudal; P, pelvis; S, sternum; H, head.

4 Discussion

The primary aim of the present study was to characterise dynamic postural stability, smoothness and symmetry in patients with vestibular hypofunction (PwVH) while performing dynamic tasks, using an objective and quantitative sensor-based approach. Our results showed significant differences between PwVH and an aged-matched HC group in gait symmetry (iHR) and dynamic stability (nRMS and AC), with a loss of gait symmetry in the sagittal plane and increased latero-lateral instability in the PwVH group. These findings emphasised the importance of the vestibular function in the maintenance of postural stability during walking [31] and feature how the symmetry of gait is altered in PwVH [26,32]. According to previous results [33] our findings revealed that vestibular hypofunction can generate asymmetry of gait during linear, curved and blindfolded paths.

The present findings showed an increase of accelerations in the ML axis for the nRMS at pelvis level, the AC from pelvis to head level and from sternum to head level during dynamic motor tasks underlining an altered normal processing of the sensory reweighting in the control of the upper body movement during gait [34]. PwVH to compensate the vestibular disorder, implement a series of postural adjustments of the entire body and the head in the pitch plane varies considerably [35]. Vestibulo-spinal pathways can be altered in patients with VH, modifying the neural plasticity of the head and trunk control mechanism [36]. Consistently, vestibular-only neurons sending bilateral projections to the spinal cord, contributing to the modulation of the vestibulo-collic reflex, which is of fundamental importance in the stability of the head during body movements [37]. This alteration can impact the multi-modal integration of the vestibular and extra-vestibular cues including visual and proprioceptive sensory signals [38] generating severe perceived dizziness as reported by the DHI scores. Interestingly, the iHR resulted altered in all three dynamic tasks suggesting that it is the most responsive index in PwVH to evaluate the gait asymmetry. These findings are consistent with the diagnosis of VH, indeed previous studies have already reported an asymmetry of plantar pressure towards the side of the lesion [39,40] especially during walking with eyes closed and an asymmetry of the arm swing during the gait in PwVH [41] underlining a whole compensation to the stability alteration. This is an important point from a rehabilitative perspective; indeed, the instrumental-based assessment could provide information about the vestibular-spinal reflex gain and its muscular modulation in PwVH. Furthermore, more dynamic and challenging tasks can better characterise the postural and gait strategies adopted after VH and allow to design of more appropriate rehabilitative training. Indeed, specific training tailored to facilitate the vestibulospinal reflex resulted effectiveness in improving the medio-lateral axis accelerations, and in improving motor control during functional activities [42].

Moderate-to-strong statistical correlations were found during the 10MWT, Fo8WT and FST between the DHI clinical test and a subset of features in the domains of postural stability and gait smoothness. These

results might indicate how self-perception of dizziness in PwVH is associated with objective impaired stability during demanding dynamic tasks like the Fo8WT and FST. Similar associations have also been reported between the DHI and spatiotemporal gait parameters which were highly associated with altered gait [22]. This is an important point since the instrumental-based assessment can support the clinician in objectifying the limitations on everyday activities and restrictions on social participation for PwVH, generally evaluated only with the DHI [43].

Instead, for the BBS significant correlations were found in the F8WT with the ML instability of the head (nRMS-H_{ML}) and in the FST with AC_{PH} (in the cranio-caudal direction) and with LDLJv in the cranio-caudal axis. No correlations were found for the other spatiotemporal and symmetry parameters. Speculating on these results, we can hypothesise that BBS is not sensitive enough to identify mild gait and balance disorders that are observed in chronic PwVH. At the same time, the correlations found during the Fo8WT underpin the usefulness of a curved path assessment to better evaluate postural stability alterations with respect to linear paths. In previous studies, gait deficits associated with turning angle, and head and trunk coordination are present in PwVH in the acute phase and persist long after the onset of vestibular loss [7,12,33,44]. These dynamic postural control alterations should be addressed through a more dynamic rehabilitative approach considering the visual suppression and vestibulo-spinal reflex training as reported in previous studies for neurological disorders [45–47]. To the best of our knowledge, this is the first study carried out with PwVH in which symmetry, stability and smoothness of gait were examined during straight, curved, and blindfolded locomotion using a body-worn network of wearable motion sensors. Although the instrumental vestibular assessment allows, with high sensitivity and specificity, the evaluation of both otolithic and semicircular canal functions, the influences of the VH on dynamic stability are still under debate. Our sensors-based approach could represent a feasible strategy in obtaining objective and quantitative information regarding the dynamic stability of the gait in PwVH. Current results must be interpreted in light of the following limitations. First, the diagnosis of VH was different for the study participants, indeed 7 patients had vestibular neuritis in the chronic phase, 3 patients had Meniere Disease in the chronic phase and 1 post-surgery vestibular neurectomy although, interestingly the sample size was appropriate for the statistical analysis of the specific gait metrics. Furthermore, we do not include the vestibular evoked myogenic potential during the instrumental assessment even though vHIT is a sensitive and specific test to diagnose VH [28,48].

5 Conclusions

In this study, we characterized the movement-related alterations during linear, curved, and blindfolded walking/stepping in PwVH combining an instrumental IMU-based with traditional clinical scales approach. An alteration of the symmetry of gait and trunk dynamic stability were found during the three motor tasks. Significant correlations were found between the DHI score and the dynamic instrumental assessment during the Fo8WT. Based on these results, combining instrumental and clinical evaluation for dynamic stability of gait alterations in PwVH is useful in thoroughly evaluating the effects of unilateral vestibular hypofunction. Further studies are needed to investigate if this approach can be considered as a rehabilitative outcome and to design more personalized rehabilitation programs in PwVH.

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