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Recurrence quantification analysis of gait in normal and hypovestibular subjects

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ABSTRACT

The study of postural control processes during locomotion may provide useful outcome measures of stability for people with unilateral vestibular hypofunction (UVH). Since nonlinear analysis techniques can characterize complex behaviour of a system, this may highlight mechanisms underlying dynamic stability in locomotion, although only few efforts have been made. In particular, there have been no studies that use recurrence quantification analysis (RQA), which can be applied even to short and non-stationary data. The purpose of this study was to develop a new method for walking balance assessment measuring the complexity of head, trunk and pelvis three-dimensional accelerations and angular velocities during normal overground locomotion by means of RQA in normal subjects and UVH patients. The results showed differential effect of upper body parts on pattern regularity, with better head than pelvis stabilization in both groups of subjects. The RQA outputs such as percent determinism and recurrence were nevertheless significantly lower in the UVH group for all measures, suggesting that body accelerations and angular velocities, although not significantly different in amplitude, were more chaotic in patients. The observed lower regularity of upper body movements in UVH is consistent with an important role of the vestibular system in controlling dynamic stability during walking. The findings suggest that RQA can be used as a quantitative tool to assess walking performance and rehabilitation outcome in patients with different balance disorders.

1. Introduction

The control of postural equilibrium is based on the integration of different sensory systems including vestibular apparatus that provides information about head movement and orientation in space. During walking, the vestibular system contributes to head and whole body orientation and stabilization through vestibulocollic reflexes (VCR) and other vestibulo-spinal mechanisms [1–3]. At the same time, balance control requires head stability so that the maximum head velocity does not exceeds the range over which the vestibulo-ocular reflexes (VOR) can enable optimal gaze control [4–7]. Indeed, upper body accelerations are gradually attenuated from the bottom to the upper portions of the body, a process that may be associated with the top-down control and recruitment of paraspinal muscles during walking [7–9]. Nevertheless, the overall dynamic stability of the whole body is achieved through the coordination of different segments including leg motion, arm-leg coupling and trunk rotation compensatory adjustments.

Evidence for the functional importance of vestibular sensors for posture and equilibrium is also provided in patients with unilateral vestibular loss that suffer from disequilibrium and tend to fall to the side ipsilateral to the lesion [10–12] as well as in patients with bilateral vestibular loss that also show balance impairments especially during walking without vision or on unstable support [7,13,14]. However, quantification of dynamic stability during locomotion represents a great challenge since classic analysis measurements such as the amplitude of trunk oscillations or interstep variability of angular motion during normal walking often fail to discriminate clearly between normal and pathological gait. In effect, often specific walking conditions are needed to identify pathological features [7,15]. Therefore, developing new complementary methods may help assessing walking performance and rehabilitation outcome in patients with different balance disorders.

While many studies reported gait-related oscillations at the head and other body segments [16–19], little is still known about the nature of these oscillations and their relationship to dynamic stability. Locomotor stability can be assessed by analyzing variability and complexity of locomotor patterns [20–23]. Nonlinear analysis techniques applied to systems exhibiting complex behaviour such as posture control, may provide insights into the mechanisms underlying dynamic stability. One such method, recurrence quantification analysis (RQA) has been applied to

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various biological phenomena and more recently to the posture control during standing [24–26]. However, few efforts have been made to apply experimental techniques derived from nonlinear dynamics to locomotion and there are no studies in literature that use the RQA for locomotion. Moreover, in contrast to other nonlinear techniques that require long duration recordings and/or strict periodicity (such as Lyapunov exponents, and orbital stability [20,27]), the RQA can provide useful information regarding the pattern and structure of system dynamics even for short duration and non-stationary data. The power of recurrence quantification analysis resides in its independence from constraining assumptions and limitations affecting other analyses. Because recurrence structures are simply tallied within the signal, there is no need to pre-condition the data by filtering, linear detrending, or some other transformation to conform to any particular statistical distribution. Recurrence analysis is not stymied by signal non-stationary, transients, outliers or noise [28]. The purpose of this study was to measure the complexity of head, trunk and pelvis three-dimensional accelerations and angular velocities during normal walking in normal subjects and unilateral vestibular hypofunction (UVH) patients by means of RQA in order to better characterize the disease-related changes in the locomotor stability.

2. Methods

2.1. Participants

Sixty-one volunteers were recruited for the study from the ENT Rehabilitation Unit of the San Raffaele Pisana Scientific Institute. Subjects were divided in two groups: the control group composed of 39 healthy persons (18 females and 21 males, age 38.4 ± 13.9 years [mean ± SD], weight 71.0 ± 13.2 kg and height 173.3 ± 9.5 cm) with no history of balance disorders and the UVH group composed of 22 subjects (8 females and 14 males, age 40.2 ± 8.4 years, weight 71.5 ± 13.9 kg and height 169.3 ± 9.9 cm) with peripheral unilateral vestibular hypofunction of various origins diagnosed by labyrinthine hypo-reflexive and prevalence in the caloric test >25%. Of the 22 patients, 11 had unilateral peripheral vestibulopathy of undetermined etiology, 3 had labyrinth ischemia outcomes, 3 underwent vestibular nerve resections resulting from acoustic schwannoma, 2 had chronic Meniere's disease, 1 had vestibular neuronitis, 1 underwent stapedectomy and 1 displayed cerebellopontine angle meningioma. At least 6 months elapsed since the onset of disease and no patient underwent vestibular rehabilitation. Patients exclusion criteria were cognitive deficits, not corrected severe visual acuity loss, joint replacement, degenerative neurological disease, whiplash injury, post-traumatic vertigo, and benign paroxysmal positional vertigo. In addition to caloric tests, all patients underwent computerized Dynamic Visual Acuity (DVA) and Gaze Stabilization Test (GST) with inVision system and Sensory Organization Test (SOT)

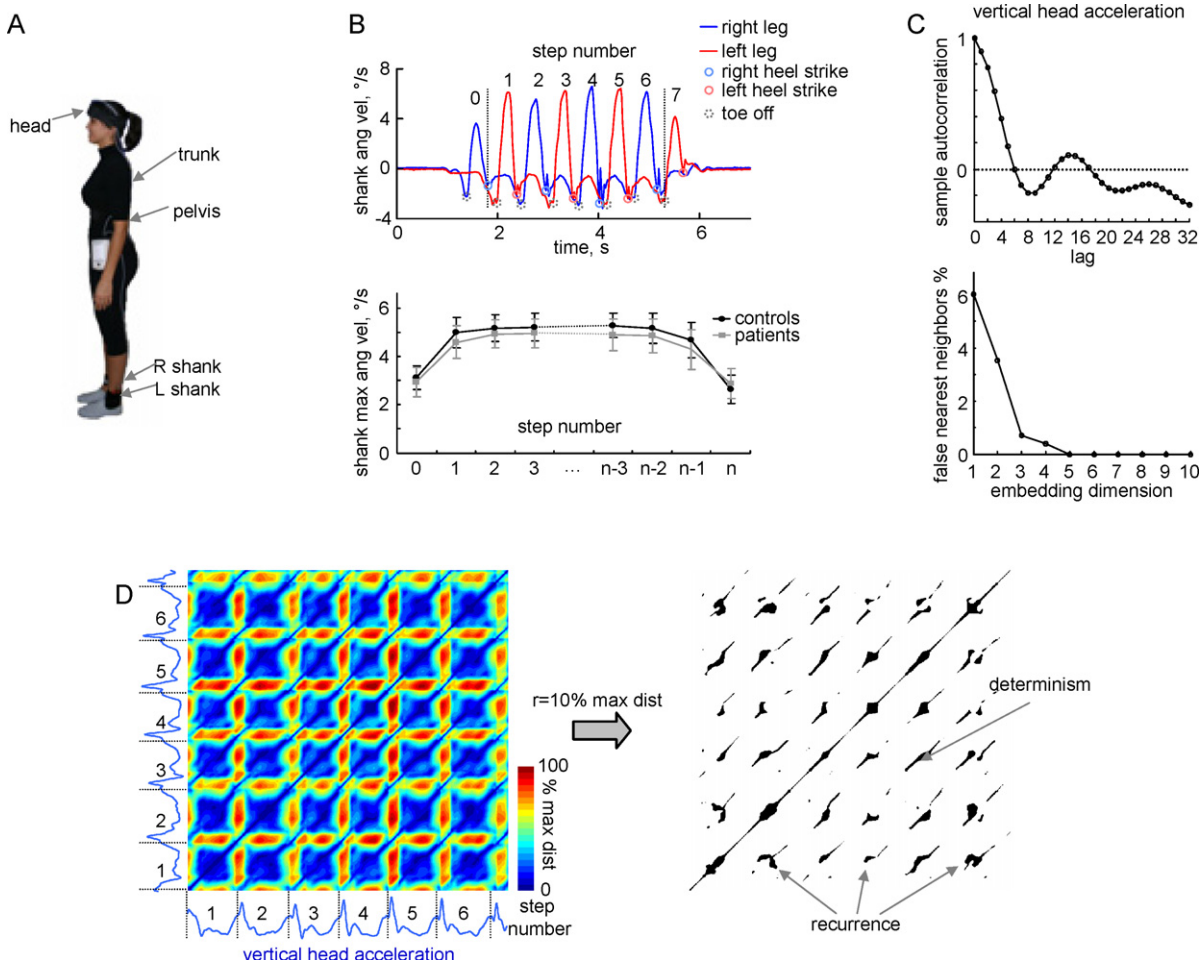

Fig. 1. Experimental setup and recurrence quantification analysis for walking. (A) Schematic view of the sensor position. Shank sensors were used to determine gait cycle events while head, trunk and pelvis sensors were used for balance control analysis. (B) Example of shank pitch angular velocities during walking in one representative control subject (upper panel). The heel strikes and steps were defined using the local minima of the shank angular velocity (color circles). The toe-off events are also shown (gray dotted circles). Seven consecutive steps (delineated between the vertical dotted lines) were analyzed in this trial, gait initiation and termination steps were discarded from the analysis. The lower panel shows the shank maximal angular velocity (mean ± SD) for both control and UVH subjects indicating that leg motion reached a 'steady state' level mostly within one step (*n* designates the number of steps in the trial). (C) Examples of the use of the autocorrelation function for optimum time lag definition (upper panel) and of the false nearest neighbors method for optimum embedding dimension selection in one representative subject. (D) Plots of the recurrence matrix generated for the head vertical acceleration time series. Darkened areas in the right panel represent recurrent points ($r \leq 10\%$ max distance). The corresponding RQA outputs (percent determinism and recurrence) were calculated. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

with Equitest system (Neurocom, Clackamas, Oregon) to assess vestibulo-ocular and vestibulo-spinal reflexes functionality [29]. The studies conformed to the Declaration of Helsinki, and informed written consent was obtained from all participants according to the procedures of the Ethics Committee of the San Raffaele Pisana Scientific Institute.

2.2. Protocol and data recording

All subjects (barefoot, eyes open) performed at least three consecutive trials. They were instructed to stand still upright for at least 5 s and, after the command "Go!", to walk with their preferred speed on a 6 m pathway. The first part of the trial, with the patient standing still, was needed to evaluate the "zero position" of the sensors.

We recorded linear accelerations and angular velocities of the head, trunk, pelvis and shank segments. Schematic view of the sensor position is shown in Fig. 1A: head (the middle of the front of the subject), trunk (the middle of the spine at T9 vertebra level), pelvis (on the middle of the spine at S1 vertebra level), left and right leg (laterally on the shank). The sensors were attached by mean of elastic bands that allowed maintaining the sensors jointly with the body segments. Shank sensors have been used to determine gait cycle events while head, trunk and pelvis sensors were used for the dynamic stability analysis.

The sensor system used was the wireless Xbus Master System (XM-B) manufactured by Xsens Technologies BV (Enschede, The Netherlands). Each sensor (MTx) was comprised of three orthogonally mounted gyroscopes, accelerometers, and magnetometers housed in a plastic casing (in the current study only the accelerometer and gyroscope were used). The signals (bandwidth: 30 Hz for acceleration and 40 Hz for angular velocities) were recorded at 50 Hz. An orientation sensor fusion algorithm calculated absolute 3-D orientation by combining output from all three components.

2.3. Data analysis

The step cycle was defined as the period between two consecutive heel strikes of both legs using the local minima of the shank angular velocity (color circles in Fig. 1B, upper panel) [30]. All consecutive steps were analyzed in each trial excluding gait initiation and termination steps (Fig. 1B). The mean walking speed was estimated as the walking distance (6 m) divided by walking duration. Since nonlinear analysis techniques are strictly related to the number of samples acquired [28], all the data were resampled in order to obtain for each trial the same number ($n = 1000$) of samples. Rotation of the acceleration vector coordinates from the sensor reference system to the global reference system allowed for correcting for the gravity component (by subtracting the gravity acceleration value 9.81 m/s^2).

2.3.1. Recurrence quantification analysis

Details regarding the RQA procedure, parameters, and variables can be found in [28]. Briefly, the acceleration and angular velocity data were embedded in m multiple dimensions using m copies of the original time series, with each copy shifted in time by integer multiples of t samples. The best value for embedding dimension was set to $m = 5$ according to the false nearest neighbors method, while the best value for time delay was selected to be $t = 6$ samples according to the first zero crossing of autocorrelation function (Fig. 1C) [26]. A distance matrix (Fig. 1D, left panel) was computed by determining the Euclidean distances between all embedded vectors. The recurrence matrix (Fig. 1D, right panel) was created by selecting a threshold (radius) of 10% of the max distance, where all cells with values below this threshold were identified as recurrent points.

The RQA variables were used to quantify the structure present in the recurrence matrix. The percent recurrence (%rec) signifies how often a trajectory visits similar locations in state space (time independent), computed as the percentage of recurrent points in the recurrence matrix. The percent determinism (%det) relates to how often the trajectory repeatedly re-visits similar state space locations (time-dependent), quantified as the percentage of recurrent points in diagonal line structures (at least four consecutive points in length) parallel to the main diagonal. Thus, %rec quantifies the number of possibly recurrent points while %det quantifies only the part of these points that recurs periodically and is related to the predictability of the dynamical system. The higher %det and %rec the more regular is the dynamic structure of the data [28].

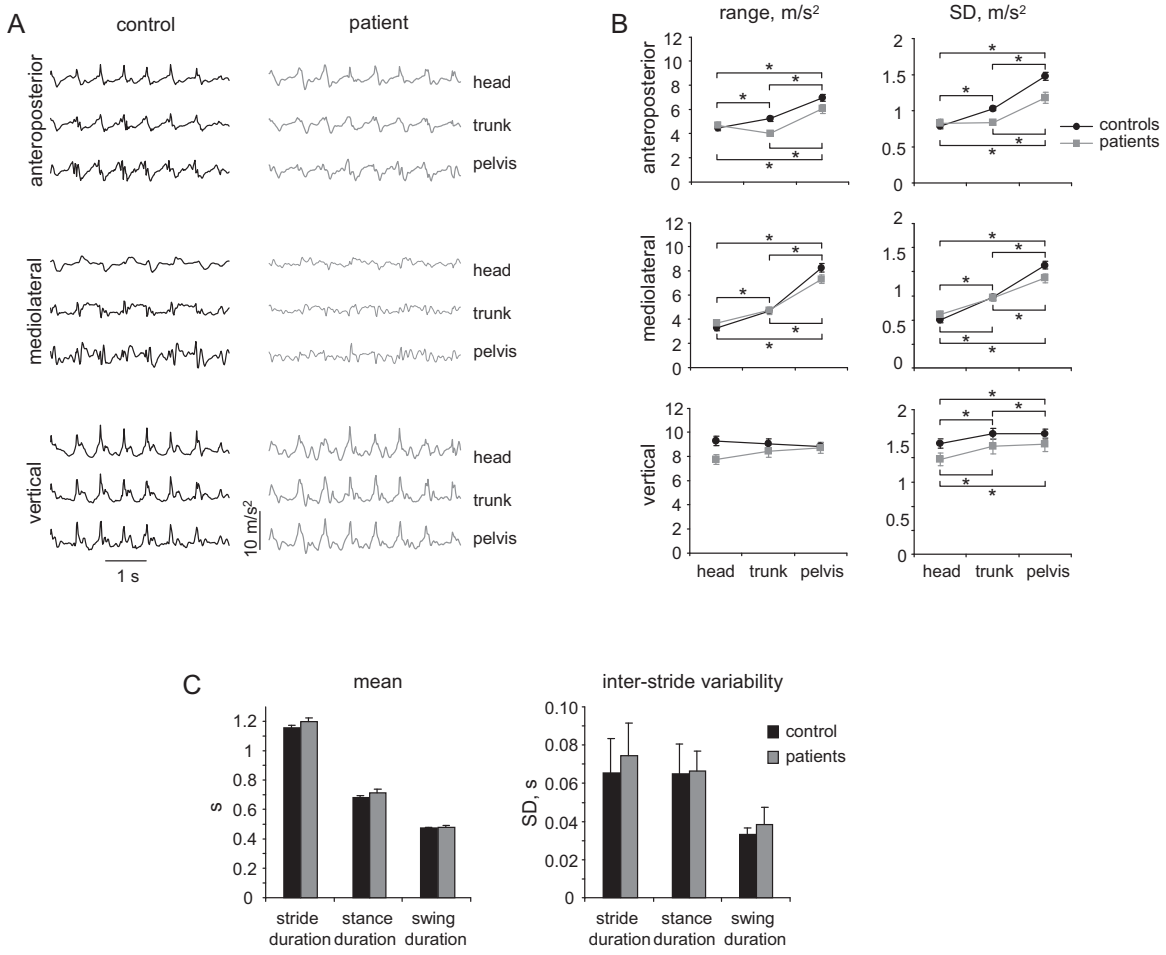

Fig. 2. Linear acceleration components during walking in control and UVH patients. (A) An example of acceleration signals (across seven consecutive steps) in one control subject and one patient. (B) Range (peak-to-peak) and standard deviation of head, trunk and pelvis accelerations for the normal and UVH subjects (mean ± SE). Asterisks denote significant differences within body segments ($p < 0.05$, Bonferroni post-hoc test). (C) Stride, stance and swing durations (mean ± SE) and their variability across strides (estimated as SD relative to the mean value) in the two groups of subjects.

2.4. Statistical analysis

Repeated-measures ANOVA was used to evaluate the effect of group and body segment. An analysis of the covariance matrix circularity was performed, and if the data failed this analysis, the Boxes Geisser-Greenhouse correction for RM-ANOVA was used. Post-hoc tests were performed by using the Bonferroni test. Reported results are considered significant for $p < 0.05$. NCSS and SPSS statistical software packages were used to perform all statistical analyses. We calculated the RQA outputs (%rec and %det) using the RQA Software 13.1 (http://homepages.luc.edu/~cwebber/). Cronbach's alpha statistics were used to evaluate %rec and %det consistency across repeated trials. Pearson correlation coefficients were used to relate the RQA outputs with the clinical evaluation of UVH patients (DVA, GST and SOT scores). All other data analyses were performed in MATLAB (Mathworks, Inc., Natick, MA).

3. Results

3.1. General gait parameters in normal and UVH subjects

The mean walking speeds in the UVH group was slightly (though not significantly) less than in the control group (4.3 ± 0.8 km/h and 3.9 ± 1.2 km/h [mean ± SD], respectively; $p = 0.19$, unpaired t-test). The mean cadence and the number of performed steps (along a 6 m walkway) also did not differ significantly between the two groups of subjects ($p > 0.05$). Fig. 2A illustrates an example of linear accelerations in one control and one UVH subject. On average, the head

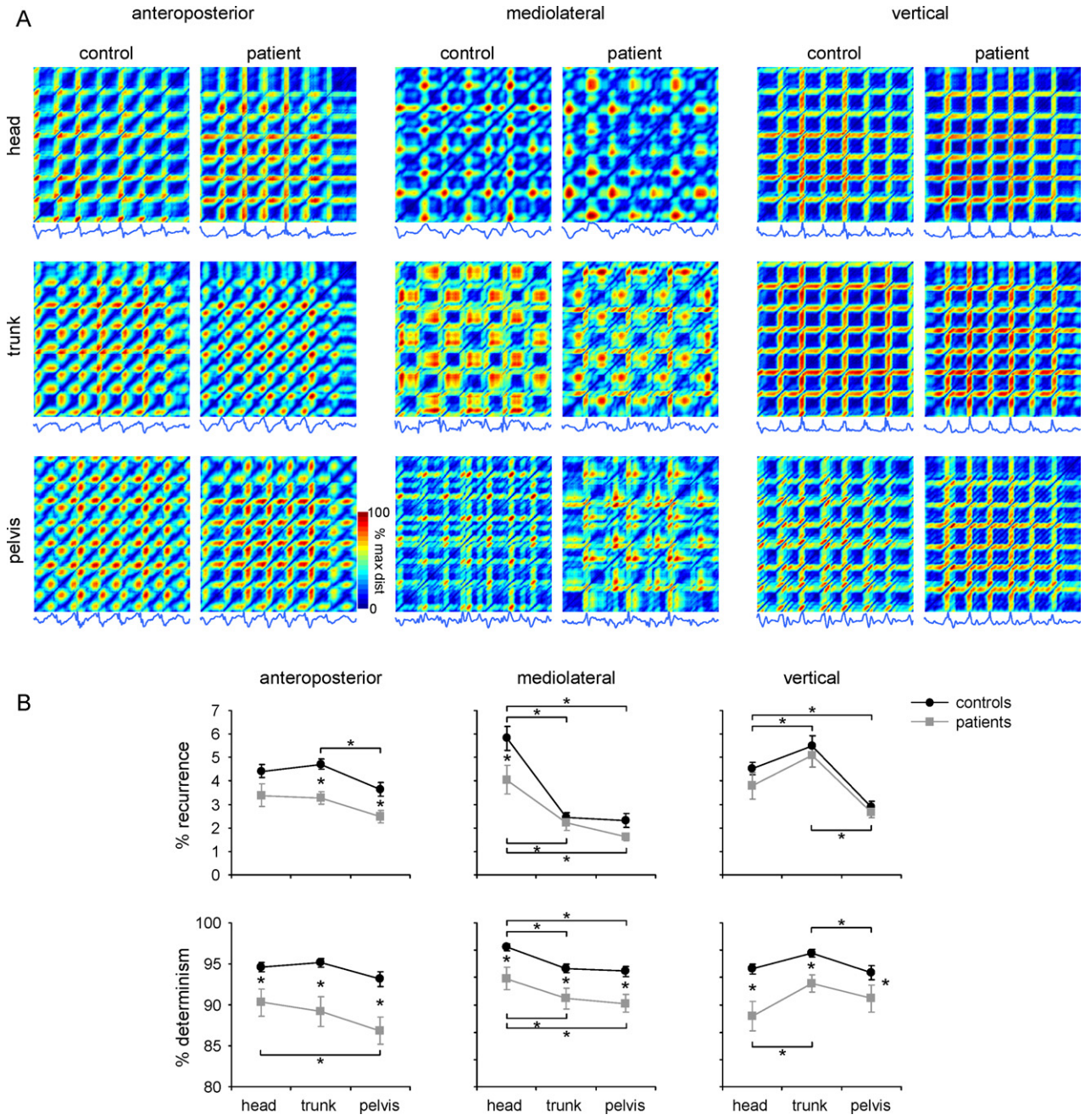

Fig. 3. Recurrence quantification analysis of the anteroposterior, mediolateral and vertical accelerations of the head, trunk and pelvis during walking in normal subjects and UVH patients. (A) Plots of the recurrence matrix generated for the head, trunk and pelvis vertical acceleration time series (normalized to the max value) for representative subjects walking at the same mean speed (~4 km/h). The same format as in Fig. 1D (left panel). Note generally more regular recurrence matrix pattern (higher intensity of the blue color) in the control subject. (B) Mean (±SE) RQA outputs (percent determinism and recurrence) for the normal and UVH subjects. Asterisks denote significant differences between groups and within body segments ($p < 0.05$, Bonferroni post-hoc tests). Note less regular patterns (significantly lower percent determinism and recurrence) in UVH patients. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Table 1
RM ANOVA results (p values) for the RQA variables (percent recurrence and percent determinism) of time series of anteroposterior, mediolateral, vertical accelerations and of roll, pitch and yaw angular velocities and for all measures combined together (6 degrees of freedom [DoF]).

		Group effect	Segment effect	Group × segment interaction
Accelerations				
%rec	Anteroposterior	<0.001**	0.001**	0.073
	Mediolateral	0.036*	<0.001**	0.071
	Vertical	0.255	<0.001**	0.752
%det	Anteroposterior	<0.001**	<0.001**	0.270
	Mediolateral	<0.001**	<0.001**	0.950
	Vertical	0.002**	<0.001**	0.575
Angular velocities				
%rec	Roll	<0.001**	0.004**	0.236
	Pitch	0.245	<0.001**	0.461
	Yaw	<0.001**	<0.001**	0.124
%det	Roll	<0.001**	<0.001**	0.032*
	Pitch	<0.001**	<0.001**	0.086
	Yaw	<0.001**	0.218	0.114
6 DoF				
%rec		0.284	<0.001**	0.540
%det		<0.001**	<0.001**	0.011*

* Significant effects are highlighted by asterisk: $p < 0.05$.
** Significant effects are highlighted by asterisk: $p < 0.01$.

oscillated less than the lower trunk in the horizontal plane in both groups of subjects (Fig. 2B), consistent with the idea of minimizing gait-related head oscillations [7,16,18]. Nevertheless, the amplitude of measured accelerometer signals, as quantified by the range (peak-to-peak, Fig. 2B, left panels) or standard deviation (Fig. 2B, right panels) of oscillations across one trial was similar ($p > 0.05$ for the effect of group, RM-ANOVA), indicating that these parameters could not discriminate the walking pattern of the two groups of subjects. The same similarities ($p > 0.05$) in the amplitude between controls and patients were found for angular velocities (not shown). There were also no significant differences in general temporal gait parameters (stride, stance and swing durations) and their inter-stride variability between the two groups of subjects (Fig. 2C). The estimation of the amplitude of oscillations (Fig. 2) is however not dependent on the temporal sequence of samples, while the RQA approach is directly related to the dynamics (order) of signals and will be considered in detail in the following sessions.

3.2. RQA of the head, trunk and pelvis three-dimensional accelerations

The purpose of recurrence plots is to visualise trajectories in phase space, which is especially advantageous in the case of complex systems. Fig. 3A shows examples of recurrence plots, with related measures of %rec and %det, obtained for head, trunk and pelvis anteroposterior, mediolateral and vertical accelerations, illustrating generally more regular recurrence matrix pattern (higher intensity of the blue color) in the control subject.

3.2.1. Anteroposterior direction

RM-ANOVA revealed a significant effect of group and of sensor (body segment) factors on %rec and %det (Table 1). The post-hoc multiple comparison procedure evidenced the following significant differences between groups and within sensors. The %rec was significantly lower for the UVH group for trunk and pelvis. In the control group, it was significantly higher for trunk vs. pelvis. The %det was significantly lower for the UVH group for all sensors and significantly higher for head vs. pelvis only in the UVH group (Fig. 3B).

3.2.2. Mediolateral direction

In both groups, the %rec was significantly higher for head vs. trunk and pelvis (post-hoc tests). In addition, the UVH subjects showed significantly lower %rec for head than the control subjects. The %det was significantly lower for the UVH group in all body segments and significantly increased in head vs. trunk and pelvis in both groups (Fig. 3B).

3.2.3. Vertical direction

The post-hoc tests revealed a significantly increased %rec for head and trunk vs. pelvis in the control group and for trunk vs. pelvis in the vestibular group. The %det was significantly lower for the UVH group for all sensors. In the UVH group, it was significantly lower in head vs. trunk.

All analyzed parameters were highly reproducible across trials ($\alpha = 0.86$ and $\alpha = 0.89$ for %rec and %det, respectively, Cronbach's test).

3.3. RQA of the head, trunk and pelvis angular velocities

Fig. 4 shows examples of recurrence plots obtained for head, trunk and pelvis roll, pitch and yaw angular velocities in subjects from the two analyzed groups highlighting the differences in segments' dynamics.

3.3.1. Roll angular velocity

RM-ANOVA revealed a significant effect of group and of sensor factors in %rec and %det. The %rec was significantly lower for the UVH group for pelvis. The %det was lower for the UVH group for all sensors. There was a tendency for pelvis to be more deterministic than head and trunk (Fig. 4B, left panels).

3.3.2. Pitch angular velocity

The %rec was higher for pelvis and trunk vs. head in both groups of subjects. The %det was lower for the UVH subjects for all body segments and higher for head and trunk vs. pelvis for both group (Fig. 4B, middle panels).

3.3.3. Yaw angular velocity

The %rec was lower for the UVH group for head. In the control group it was significantly higher for head and trunk than pelvis. The %det was significantly lower for all segments in the UVH group.

As in the case of linear accelerations, the analyzed RQA parameters for angular velocities were also highly reproducible across trials ($\alpha = 0.80$ and $\alpha = 0.91$ for %rec and %det, respectively, Cronbach's test).

3.4. RQA of the head, trunk and pelvis combined (acceleration + velocity) measures

Fig. 5A shows examples of recurrence plots obtained combining all six measures (three accelerations and three angular velocities) for each segment. The two RQA measures show somewhat different behaviour (Fig. 5B). The %det captured better the differences between control and UVH subjects since the differences in %det between the two groups were highly significant for all segments (Fig. 5B), likely because this measure, in contrast to %rec, is strictly related to periodicity.

Dividing the patients in two subgroups according to the magnitude of the vestibular deficit (Fig. 5C, group A, 7 subjects with caloric prevalence <50%, and group B, 11 subjects with caloric prevalence >75%) resulted in a significant effect of group ($p < 0.001$) and group × segment interaction ($p < 0.001$) on the %det but not on the %rec ($p = 0.102$ and $p = 0.479$, respectively). Moreover, the %det of all segments significantly ($p < 0.05$) correlated with DVA ($r = -0.48$, -0.54 and -0.43 for the head, trunk and pelvis, respectively), GST ($r = 0.37$, 0.51 and 0.35) and SOT C6 trial ($r = 0.44$, 0.40 and 0.31) scores.

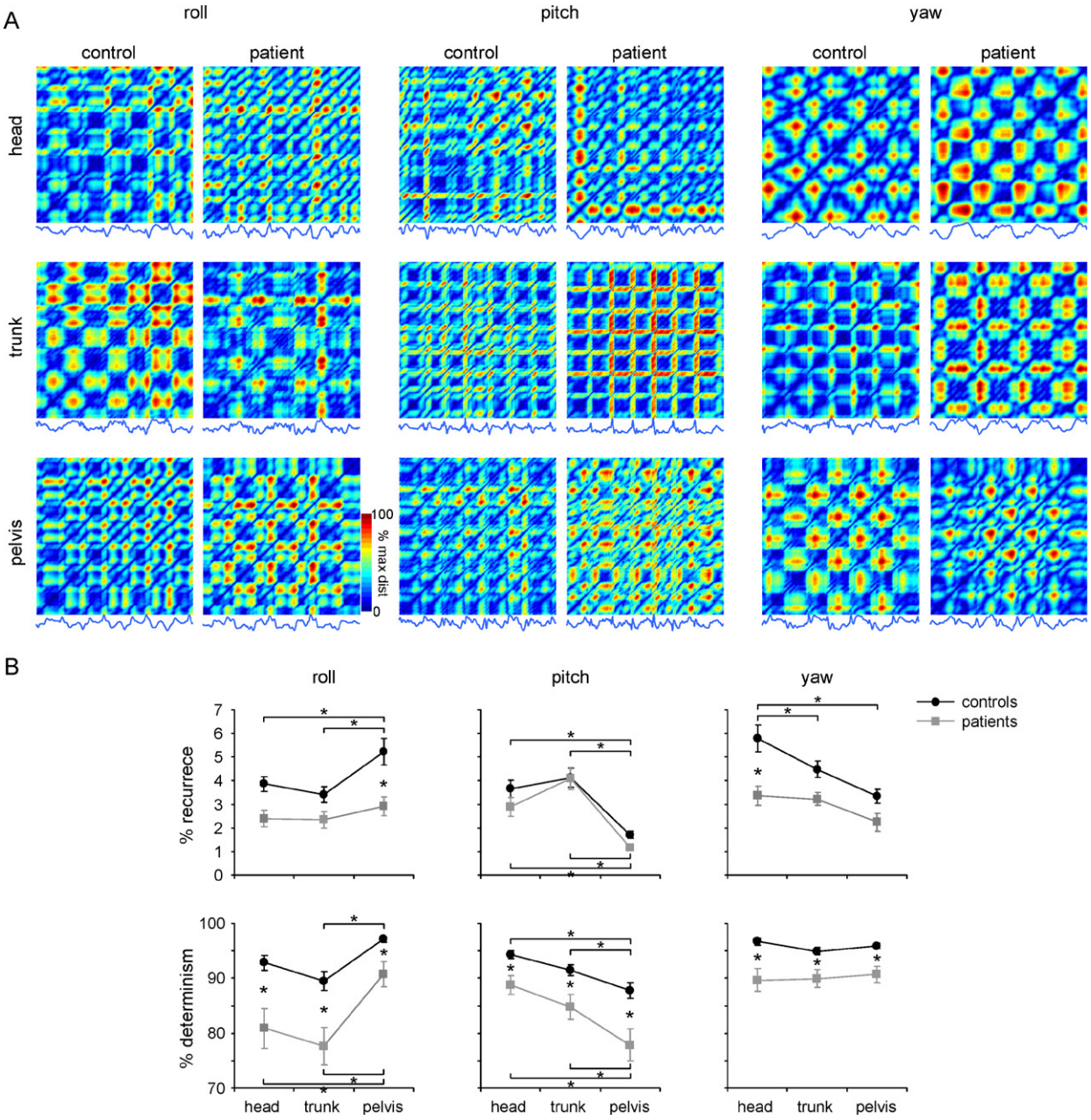

Fig. 4. Recurrence quantification analysis of the roll, pitch and yaw angular velocities of the head, trunk and pelvis during walking in normal subjects and UVH patients. The same format as Fig. 3. Note lower RQA outputs (percent determinism and recurrence) in UVH patients.

4. Discussion

The aim of this study was to investigate, by mean of nonlinear analysis techniques such as RQA, the dynamic of upper body segments, acquired through inertial sensors, during walking in healthy subjects and in persons with vestibular hypofunction. This study represents the first attempt to apply the RQA method to quantify balance control in human locomotion. We used this method to assess the dynamic structure of body motion and complexity of locomotor patterns (head, trunk and pelvis accelerations and angular movements) during normal walking in normal subjects and UVH patients.

The recurrent plots for one-dimensional measures (Figs. 3 and 4) reflected the cyclical nature of gait activity as revealed by high values of determinism and recurrence typical of periodical phenomena. The recurrence quantification analysis revealed that this 'regularity' is less stable in subjects who suffer for vestibular hypofunction, as evidenced by generally lower values in all RQA parameters for most measures acquired (Fig. 3B and 4B) consistent with lower movement regularity and potential balance impairments in the vestibular patients [7,10–13]. There was also a tendency for the head motion to be more regular (higher %rec and %det) than pelvis and trunk in the horizontal plane (anteroposterior and mediolateral directions) for all groups of subjects, while for the vertical direction the effect was different, particularly in the UVH subjects (Fig. 3B), in harmony with the idea of minimizing gait-related head oscillations [7,16,18]. It is also worth noting that the amplitude and standard deviation of measured accelerometer signals was similar for patients and controls (Fig. 2), indicating that these parameters could not discriminate the walking pattern of the two groups of subjects.

Combining all six measurements into one high-dimensional vector to derive a single recurrence plot per subject confirmed generally lower gait stability in the UVH subjects (Fig. 5). The head

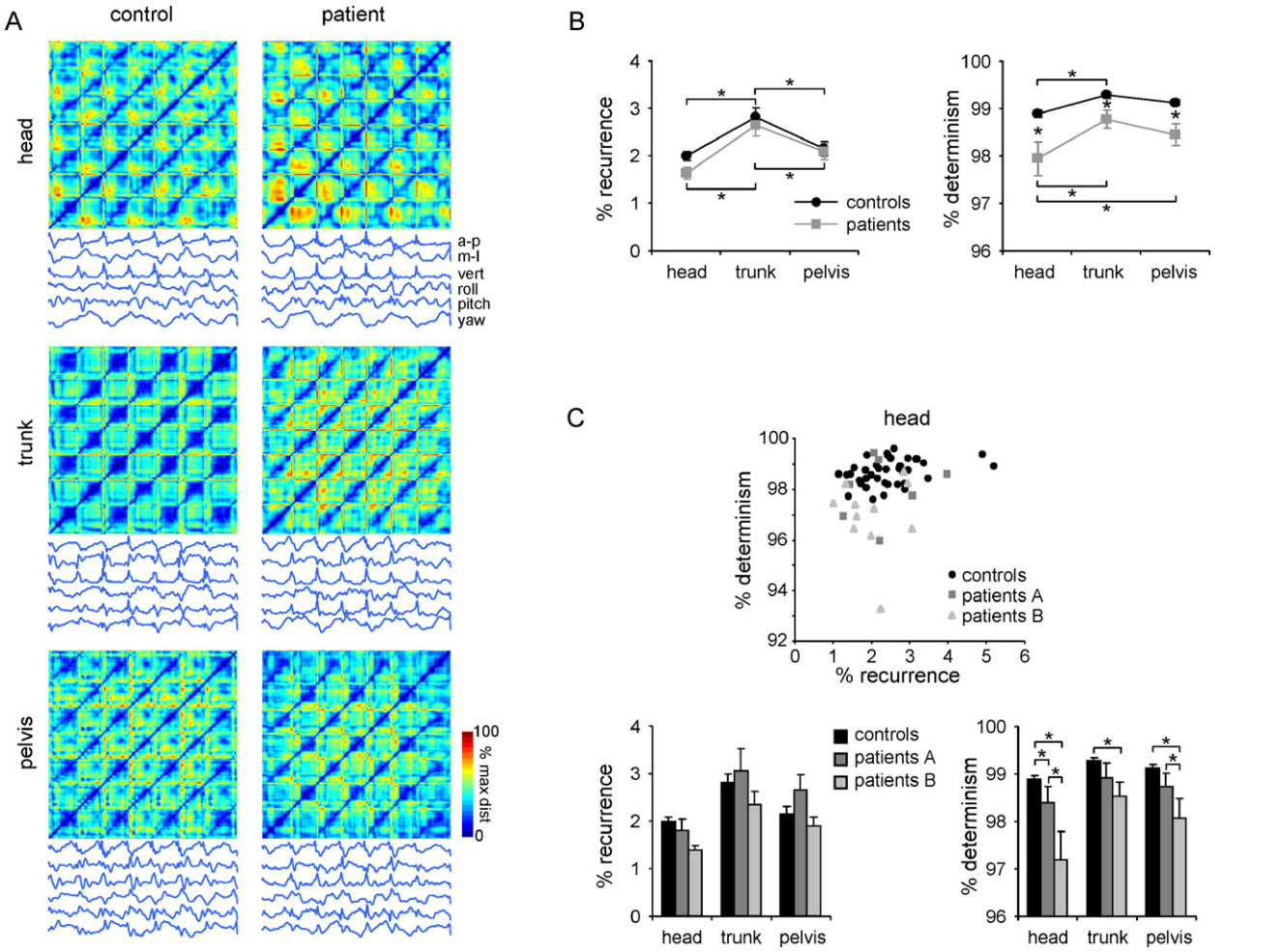

Fig. 5. Recurrence quantification analysis combining the measures of all 6 degrees of freedom (3 accelerations and 3 angular velocities, normalized to their range). (A and B) The same format as Figs. 3 and 4. (C) Example of the distribution of %det and %rec parameters for the head segment (upper panel) and means (±SE) of the RQA outputs (lower panels). UVH patients were subdivided into two groups: caloric prevalence <50% (group A, $n = 7$) and >75% (group B, $n = 11$). Asterisks denote significant differences between groups ($p < 0.05$, Bonferroni post-hoc tests).

demonstrated the more significant effect in patients (Fig. 5B, lower panel), a process that may be associated with the top-down control and recruitment of paraspinal muscles and with the fact that the principal information of vestibular nuclei reaches the cervical part of the spinal cord, through the vestibulo-spinal tracts [7,9]. Event though the distribution of the %det and %rec parameters showed an overlap between the groups (Fig. 5C, upper panel), the %det parameter for 10 patients was lower than the minimal value found for the control group. Comparing the RQA with vestibulo-ocular and vestibulo-spinal reflexes functionality measures revealed a correlation of the %det with the magnitude of the vestibular deficit (Fig. 5C). Therefore, the %det parameter is suitable for potential risk quantification and rehabilitation outcome measurements.

The observed lower regularity of upper body movements (significantly lower RQA outputs, Figs. 3–5) in the UVH patients is consistent with the important role of the vestibular system in controlling dynamic stability during walking. The findings suggest that the RQA may prove useful as a quantitative tool to assess walking performance (Fig. 5C) and rehabilitation outcome in patients with different balance disorders.

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Conflict of interest

There are no conflicts of interest.

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