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ORIGINAL MANUSCRIPT

Walking towards the future: Exploring OpenTUG's validity in automatic walking activity analyses and the relationship to cognition in vestibular patients

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Abstract

Vestibular disorders impair body orientation and spatial navigation, often causing cognitive and affective symptoms, reducing quality of life. Traditional assessments involve time-consuming physiological and neuropsychological evaluations. This study investigates the feasibility and validity of applying a 2D human pose estimation (OpenTUG) to automatically analyze the walking activity of patients with vestibular disorders. Forty-eight patients undergoing treatment for vestibular disorders and 26 mean age-matched controls performed the TUG at normal, slow, and fast walking speeds; neuropsychological evaluations assessing attention, and quality-of-life questionnaires. Patients required significantly more time and steps to complete the TUG than controls at normal and slow speeds (e.g., normal speed: 7319 ms vs. 5976 ms, $p = .002$). Automated OpenTUG and manual analyses were highly correlated (time: all $r > .94$, $p < .001$; steps: all $r > .74$, $p < .001$). Patients reported higher dizziness-related handicap (median DHI total: 30 vs. 0, $p < .001$) and psychological symptoms (median HADS total: 12 vs. 8, $p = .005$). Exploratory analyses revealed moderate correlations between TUG measures and attentional performance (Spearman's $r = .30$–$.54$, $p < .05$–$.01$), as well as postural stability indices (e.g., unstable platform with eyes open: $r = .38$–$.57$, $p < .05$–$.01$). These findings demonstrate the feasibility and validity of using OpenTUG to automatically extract clinically relevant gait parameters. The observed associations between TUG performance, attentional measures, and postural stability highlight the potential of combining simple walking tasks with pose estimation as a rapid, cost-effective preliminary assessment of vestibular patients' difficulties.

Keywords Posture · Vestibular loss · Deep pose estimation · Cognition · Algorithm · AI

Introduction

Over the course of a lifetime, each of us has at least a one-in-three chance of experiencing balance disorder caused by vestibular impairment (Agrawal et al., 2009, 2013). This chance increases with age or the presence of additional disorders such as hearing loss (Agrawal et al., 2020; Bisdorff et al., 2013; Grill et al., 2013; Neuhauser et al., 2005). Although our balance system has a remarkable ability to compensate for vestibular impairments due to the sensory plasticity (Curthoys, 2000; Lacour et al., 2016; Macdougall & Curthoys, 2012), several associated costs can occur such as increased risk of falls, cognitive deficits and reduced quality of life (Besnard et al., 2015; Bigelow & Agrawal, 2015; Enloe & Shields, 1997; Hitier et al., 2014; Obermann et al., 2023; Popp et al., 2017; Smith, 2022; Smith & Darlington, 2013; Smith & Zheng, 2013; Whitney et al., 2004).

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Previous research has sought to characterize the physical, cognitive, and quality-of-life consequences of vestibular impairments, often through extensive and time-consuming physiological and neuropsychological assessments. Yet, balance, fall risk, and potential cognitive difficulties can also be evaluated using the Timed Up and Go (TUG) task, one of the most common clinical tools to assess mobility, balance, and locomotor performance (Mathias et al., 1986; Morris et al., 2001; Podsiadlo & Richardson, 1991; Schoppen et al., 1999). Although its application in vestibular research has been relatively scarce, available studies demonstrate that the TUG is feasible and clinically useful in these populations. For instance, it reliably identifies fall risk in patients with slower times (Whitney et al., 2004) and captures functional improvements following rehabilitation in both unilateral and bilateral vestibular loss (e.g., Brown et al., 2001; Gill-Body et al., 2000; Karapolat et al., 2014). Together, these findings confirm the TUG's sensitivity to mobility impairments in vestibular disorders, though most investigations have focused on fall risk and rehabilitation outcomes rather than on potential cognitive correlates.

In parallel with this observation, growing evidence supports the feasibility of accurately quantifying the time needed for specific movements during walking. Originally, the TUG measurement was based on the total time taken to perform the full task, recorded with a stopwatch, and sometimes combined with qualitative clinical observations. Today, more accurate quantitative assessments of the TUG have been developed using new technologies. For example, wearable kinematic sensors attached to the body provide a novel, detailed, and responsive evaluation of patients' movements.

Wearable inertial sensors have allowed more precise quantification of gait features such as stride length and angular velocity (e.g., Howcroft et al., 2013; Mancini et al., 2013; Montesinos et al., 2018; Weiss et al., 2011). Outside the vestibular field, these measures have been linked to fall risk and cognitive decline, though findings vary across studies (Greene & Kenny, 2012; Shany et al., 2015). Within vestibular populations, Sankarpandi et al. (2017) found that sensor-based parameters could distinguish fallers from non-fallers, and Kim et al. (2021) identified specific turning impairments. Overall, while sensor-based approaches show promise, inconsistencies regarding the most informative gait parameters highlight the need for alternative methods to clarify better gait–cognition–balance relationships in vestibular disorders.

While wearable kinematic sensors provide a more accurate evaluation of the patient's dynamic movements, the wearing of these sensors can temporarily alter walking patterns and gait speed (Carvalho et al., 2020). For vestibular patients who need to compensate their deficits through the use of other sensory systems (Lacour et al., 2016), alterations to proprioceptive feedback might have a strong influence on vestibular loss patients' postural control. Therefore, alternative advanced measurement methods are needed.

The latest technologies for capturing movements utilize Video-Based Pose Estimation (VBPE) to measure walking without the need for wearable sensors. VBPE is a powerful image analysis method allowing the detection and tracking of various body parts or key point positions of a person in a video sequence. It allows the analysis of movements and postures by identifying and following specific points on the body, such as joints, limbs, and facial features, through sequences of frames in a video. The absence of any wearable sensors allows the participants to walk exactly as they do in their everyday life.

VBPE has recently been applied to diverse groups, including healthy adults, geriatric patients, individuals with dementia, and patients with Parkinson's disease (e.g., Dubois et al., 2018; Kondo et al., 2024). These studies consistently demonstrate the feasibility of automated TUG analysis and its capacity to capture subtle motor impairments. Several techniques have been developed to extract gait characteristics, with diverse standard or in-depth camera types combined with various methods to determine depth. VBPE algorithms mostly use convolutional neural networks (CNN) applied through different software such as DeeperCut, DeepLabcut, Anipose, or OpenPose to videos from standard cameras, Microsoft's Kinect or Intel's RealSense cameras (Salchow-Hömmen et al., 2022). However, to the best of our knowledge, this recent explosion of new combined technologies has not yet been used for the assessment of vestibular patients.

Eventually, previous research outside the vestibular literature has also shown that reduced TUG walking performance (measured manually or automatically) has been associated with increased fall risk but also with cognitive decline in normal ageing (Greene & Kenny, 2012), in post-stroke patients (Yu et al., 2021), and in several neurodegenerative diseases such as Alzheimer's or Parkinson's (Ansai et al., 2017; Viteckova et al., 2019; Yoo et al., 2020). In the vestibular field, however, only a reduced number of studies have investigated the effects of TUG linked to cognitive or reduced quality of life symptoms caused by vestibular loss (VL), and mixed results are observed. Herssens et al. (2021) used the classical TUG task, as well as a cognitive and motor-adapted version of the TUG, with a group of patients with bilateral vestibulopathy (BVP). In the cognitive and motor versions of the TUG, participants performed the TUG, and either counted backwards in steps of three from a randomly selected number between 80 and 100 (cognitive TUG) or had to carry a full cup of water (motor TUG). Although BVP fallers tended to report worse self-perceived handicap and performed slightly worse than BVP non-fallers, no significant differences were found between fallers and non-fallers for each of the TUG versions. Those results differ from previous studies showing that the TUG was useful to discriminate fallers from non-fallers in its original version (Brown et al., 2001; Gill-Body et al., 2000; Karapolat et al., 2014). In another study (Bosmans et al., 2022), used the TUG and other measures to explore multiple vestibular characteristics of patients with Bilateral VL and their potential associations with cognition. Patients with VL showed worse cognitive performance than controls, but the impairments were not related to the TUG results, raising the question if the TUG could be predictive or not of cognitive symptoms in VL patients.

Overall, the literature supports the TUG as a relevant clinical tool, yet findings in vestibular populations remain inconsistent: while some studies report its usefulness in discriminating fallers and detecting rehabilitation effects, others fail to establish clear associations with cognitive or functional outcomes. This heterogeneity suggests that the predictive value of the TUG in vestibular research remains uncertain, thereby warranting novel approaches. In this study, we examine the usefulness of an automated analysis of TUG performance by comparing manual and automatic scoring in patients with vestibular disorders and healthy controls, and by exploring its associations with potential cognitive impairments related to vestibular dysfunction.

Materials and methods

Design

This was an experimental single-center prospective study, recruiting over 2 years, patients with mixed vestibular disorders currently undergoing physiological treatment at Cliniques Universitaires Saint-Luc, Brussels, Belgium. Prior to the beginning of the study, participants were briefed, provided written consent, and completed demographic inquiries. Subsequently, their symptoms were evaluated using randomized subjective and objective neuropsychological assessments. Subjective measures were recorded through questionnaires, measuring physical, functional, emotional (D.H.I, Jacobson & Newman, 1990), and cognitive (NVI, Lacroix et al., 2016) impacts of the vestibular disorders. Quality-of-life symptoms (such as anxiety and depression) were also recorded with the French version of the HADS scale (Lépine et al., 1985; Zigmond & Snaith, 1983). Objective measures assessed phasic alertness and divided attention (both visual and auditory) using the Test for Attentional Performance (TAP test, Zimmermann & Fimm, 2002). Walking activity was evaluated with the Timed "Up and Go" (TUG) test (Podsiadlo & Richardson, 1991) while being recorded with an Intel RealSense depth camera. Patients were instructed to perform the TUG at three speeds: first, a regular pace, then a slower pace than usual, and then a faster pace than usual. To compare the manual analysis of TUG measurement, a 2D human pose estimation method (OpenTUG) was applied to automatically extract the time and the number of steps taken by the participant during the TUG.

Participants

A total of 100 participants were initially recruited (62 patients with vestibular disorders and 38 healthy controls). Data from 26 individuals were excluded due to technical issues (e.g., corrupted or missing TUG video recordings) and/or incomplete cognitive or questionnaire data (e.g., missing questionnaires, technical problems with the TAP tasks). The final sample, therefore, comprised 48 patients (29 women) and 26 healthy controls (18 women). These exclusions were attributable solely to technical or missing data and were not related to participants' clinical or demographic characteristics. Patients agreed to perform a simple Timed-Up & Go (TUG) task and a neuropsychological evaluation (subjective affective and objective measures). To document their vestibular affection, retrospective data from their previous neuro-ontological and postural examination performed within the last year on average, were collected (audiometry, caloric testing, cervical/ocular vestibular evoked myogenic potentials, Video Head Impulse Test, dynamic posturography -Multitest Framiral-), see Table 1 in the supplementary materials for detailed clinical data. Due to ongoing vestibular testing for most participants, the specific type of vestibular disorder was not always initially determined, and all the physiological assessments were not available. For example, only 31 of the 48 patients performed the dynamic posturography assessment, providing a postural instability index (PII) in six different conditions (A-B-C: stable platform, eyes open, eyes closed, eyes open with optokinetic stimulation; D-E–F: same conditions with unstable platform). See Table 2 in the supplementary materials for the average score of postural stability index in each condition.

The patient's ages ranged from 25 to 85 years old (average age: women = 54.3, men = 62.1, total = 57.4), with 54% of them wearing glasses and 85% stating being right-handed. Most participants did not use hearing devices (93%). The majority were fluent in French (75%) (production and comprehension). On average, participants were 169.5 cm tall and weighed 69.5 kg. Education levels varied, with most having at least a master's degree (48%).

Healthy controls were included if they reported no history of vestibular, neurological, or psychiatric disorders, no balance or hearing impairments, and no use of medication likely to affect cognitive or motor performance; all controls also had normal or corrected-to-normal vision sufficient for task execution. Patients were included if they had a clinically confirmed vestibular disorder and were undergoing or had recently undergone vestibular assessment and treatment. Exclusion criteria were the presence of neurological or psychiatric disorders, use of medication likely to affect cognitive or motor performance, and uncorrected visual impairments that could interfere with the tasks.

The study was approved by the ethics committee of Cliniques Universitaires Saint-Luc-UCLouvain (ref: 2021/16MAR/127—B4032021000039). A control group of 26 average age-matched healthy controls without known vestibular, neurological, or psychiatric disorders (18 women, average age: women = 53.7, men = 59.6, total = 55.5, 46% of them wearing glasses and 76% stating being right-handed) also performed the Timed-Up & Go (TUG) task and the neuropsychological evaluation.

Walking task and automatic analyses

To evaluate walking abilities, participants performed the Timed-Up & Go (TUG, Podsiadlo, 1991), a reliable simple task initially designed to assess mobility, stability, and motor performance of participants. Participants were asked to stand up from a chair, walk until a line on the ground marked at 3 m, turn, go back to the chair, and sit down again. They had to perform the task four times, the first as a practice trial, followed by three measures at the three different speeds (normal, slow, and fast speed). The practice trial was used to ensure that the instructions were correctly understood. The practice trial results were not analyzed. Patient's performances were videorecorded with an Intel RealSense depth camera D435i to capture their movements, and manual time recording of time taken (in seconds) and number of steps was carried out by the experimenters.

Complementary to manual experimenter recording, a 2D human pose estimation method (OpenTUG) was applied to automatically extract the time and the number of steps taken by the participant during the TUG task. OpenTUG builds on OpenPifPaf (Kreiss et al., 2019), a bottom-up method for multi-person 2D human pose estimation, predicting timing and the number of steps of the person from an accurate skeleton estimation of the human body. OpenPifPaf uses PIF (Part Intensity Field) to find keypoint locations of the body and PAF (Part Association Field) to make connections between the keypoints to form a full-body representation (Kreiss et al., 2019). OpenTUG uses a combination of keypoint locations through time to extract the timing of the actions and count the number of steps. The horizontal locations of the shoulders were used for finding the point in time when the walk towards the camera ended and the person turned around. End-of-sitting was estimated by finding local minima of the distance between the shoulders and the hips, as it is the lowest when the person is furthest from the camera, which is the time when the person finishes the sitting process. To determine the end-of-standing, OpenTUG created a signal based on the vertical distance between the hips and knees, normalized by the vertical distance between the ankles and knees. It then takes the local maximum of the first derivative of this signal. The first local maximum after the end of the sitting is considered the end of the standing. The intuition is that during the process of standing up, the calculated signal rises until the person is fully standing up. For counting the steps, OpenTUG considers the speed of the ankle movements, with a crossing of the speed from the two ankles indicative of one step. An attached video provides an overview of the depicted methods.

Neuropsychological evaluation

The neuropsychological evaluation included three subjective measurements, with the goal to assess self-perceived physical, functional, cognitive and emotional effects of the vestibular disorders. The French adaptation of the gold standard *Dizziness Handicap Inventory*—DHI (Jacobson & Newman, 1990; Nyabenda et al, 2004) was used to assess the perceived impact of vestibular system disorders on daily life using 25 items, each scored on a five-point Likert scale. This questionnaire covers three main areas of difficulty: functional, physical, and emotional aspects related to dizziness and instability. Subjective perception of cognitive difficulties was covered by the *Neuropsychological Vertigo Inventory – NVI* (Lacroix et al., 2016), using 28 items, each scored on a five-point Likert scale and divided into seven distinct subscales measuring attention, memory, emotion, space perception, time perception, vision, and motor abilities. Anxiety and depression symptoms were measured with the French version of the Hospital Anxiety and Depression Scale (HADS) (Zigmond & Snaith, 1983), using a 14-item self-assessed questionnaire, each with a four-point response Likert scale, with measures divided into an Anxiety subscale (HADS-A) and a Depression subscale (HADS-B) (both containing seven items).

Complementary to these subjective measurements, objective cognitive measures assess two main components of attentional abilities with the Alertness and Divided Attention tasks from the TAP (Zimmermann & Fimm, 1995). Participants sat in front of a computer screen and responded by pressing a reaction time button to visual and auditory inputs. For the alertness task, they responded as fast as possible when a cross appeared on the screen with or without an alert sound being played before the appearance of the cross. For the Divided Attention Task, they responded as fast as possible when a combination of four crosses formed a square on a 4 × 4 matrix while listening to two distinct sounds that followed each other. They had to respond whenever one of the sounds was heard twice. In both tasks, median reaction time and standard deviation of the median (regularity) were recorded in milliseconds. Slow reaction times and large standard deviations indicate more difficulties for the participants.

Statistical analyses

Statistical analyses were performed using IBM Statistical Package for the Social Sciences (SPSS, Chicago, IL, USA, version 27.0) and JASP statistics package (version 18.3, available online at https://jasp-stats.org/; JASP Team, 2024 Love et al., 2019). The study design and analysis were not pre-registered. The anonymized raw data are shared here: https://doi.org/10.6084/m9.figshare.28617062.v1. The usefulness of the 2D human pose estimation method (OpenTUG) for vestibular patients was evaluated in four steps: First, to demonstrate concurrent validity between OpenTUG automatic and manual steps/time analyses, we compared the Mann–Whitney version of the Wilcoxon rank-sum test applied to test for statistical differences between manual and automatic steps/time analyses during the TUG task. Second, to support this comparison, we run Spearman's correlation analyses between automatic and manual steps/time analyses. Third, to characterize our patient sample, we performed the Mann–Whitney test to compare patients and controls' neuropsychological assessment (subjective and objective measures). Fourth, we explore the relationship between walking tasks, neuropsychological assessments, and postural measures. Because of the different sample sizes between our groups, and violations of normality for most dependent variables (verified with the Kolmogorov–Smirnov test), nonparametric analyses were used for intergroup performance comparisons. For correlation analyses, Spearman's coefficients (*r*) were interpreted as weak if less than 0.37, moderate if between 0.38 and 0.67, strong between 0.68 and 0.88, and very strong above 0.89. To accommodate the multiple statistics, we adjusted the *p* values using the false discovery rate method (Benjamini & Hochberg, 1995; Curran-Everett, 2000).

Results

Group performance comparisons for manual and automatic steps/time analyses during the TUG task

Compared to healthy controls, patients took significantly more time and performed more steps to perform the TUG task than healthy controls at normal and slow speeds, regardless of the method used (manual or automatic). At fast speeds, patients also took more time and performed more steps than healthy controls, but this difference was only statistically significant for the time of movement with manual analyses (see Fig. 1 and Table 1 for detailed information).

Table 1 Detailed results of intergroup performance comparisons for manual and automatic steps/time analyses during the TUG task

Task	Manual				Automatic			
	Median, SD, *n* healthy controls	Median, SD, *n* vestibular patients	Mann–Whitney U *p* value, effect-size (rank biserial correlation)	Adjusted *p* value*	Median, SD, *n* healthy controls	Median, SD, *n* vestibular patients	Mann–Whitney *U p* value, effect-size (rank biserial correlation)	Adjusted *p* value *
TUG								
Total time (ms)								
Normal speed	(5976.0 ± 1505.4), *n* = 26	(7319.0 + 1773.9), *n* = 48	**.002**; 0.429	**.004**	(5840.0 ± 1740.5), *n* = 26	(7650.0 + 2142.8), *n* = 48	**<.001**; 0.502	**.001**
Slow speed	(8294.5 ± 2968.1), *n* = 26	(10,400.0 + 5395.3), *n* = 47	**<.001**; 0.511	**.004**	(7870.0 ± 3213.8), *n* = 26	(7650.0 + 5819.6), *n* = 48	**<.001**; 0.545	**.001**
Fast speed	(4755.5 ± 1556.3), *n* = 26	(5650.0 + 1677.0), *n* = 48	**.031**; 0.306	**.037**	(4650.5 ± 2186.3), *n* = 26	(5985.0 + 2148.4), *n* = 48	.178; 0.192	.178
Total steps								
Normal speed	(10.0 ± 1.9), *n* = 26	(12.0 ± 3.0), *n* = 48	**.009**; 0.365	**.013**	(11.0 ± 3.0), *n* = 26	(13.0 ± 4.2), *n* = 48	**<.001**; 0.477	**.001**
Slow speed	(11.0 ± 2.9), *n* = 26	(13.0 ± 4.6), *n* = 48	**.002**; 0.440	**.004**	(13.0 ± 5.9), *n* = 26	(18.0 ± 8.5), *n* = 48	**<.001**; 0.467	**.001**
Fast speed	(9.5 ± 2.4), *n* = 26	(10.0 ± 3.1), *n* = 48	.144; 0.204	.144	(8.0 ± 4.3), *n* = 26	(10.0 ± 4.2), *n* = 48	**.046**; 0.281	.055

*p value adjusted according to Benjamini and Hochberg procedure (1995) for Mann–Whitney *U* tests. Effect sizes are given by the rank biserial correlation. Significant effects are represented in bold

Correlations between automatic and manual steps/time analyses

The total time taken for executing the TUG task at different speeds was highly significantly correlated between manual recording and OpenTUG estimations for all participants (patients and controls, $n=74$). All correlations were above.94, $p<.001$.

The number of steps taken for executing TUG task at different speeds was strongly significantly correlated between manual recording and OpenTUG estimations for all participants (patients and controls, $n=74$). All correlations were above.74, $p<.001$). See Fig. 2 for the detailed measures.

Intergroup performance comparisons for neuropsychological assessment

Subjective measures

Compared to healthy controls, patients expressed significantly more physical and emotional complaints (DHI, HADS), although the difference on the HADS anxiety subscale did not remain significant after FDR correction ($p=.068$). For the NVI, patients expressed more subjective vision, motor and emotion complaints, while the total score, space perception, time perception, attention and memory subscales did not show group differences (see Table 2, Fig. 3).

Objective measures

The alertness task showed no differences in tonic alertness between patients ($Mdn=247.0$, $IQR=64.0$, $n=41$) and healthy controls ($Mdn=268.5$. $IQR=59.25$, $n=26$), $U=412.5$, $p=.12$, or between phasic alertness (with the auditory signals) for patients ($Mdn=246.0$, $IQR=56.0$, $n=41$) and healthy controls performances ($Mdn=257.0$ $IQR=55.50$, $n=26$) $U=444.5$, $p=.26$. Following the same trend, the divided attention task showed no differences between patients and healthy controls for visual reaction time (patients $Mdn=773.00$, $IQR=121.0$, $n=39$; healthy controls $Mdn=787.0$ $IQR=126.0$, $n=26$), $U=456.0$, $p=.50$), auditory reaction time (patients $Mdn=604.0$, $IQR=117.5$, $n=39$; healthy controls $Mdn=649.0$. $IQR=124.5$, $n=26$), $U=369.0$, $p=.07$ and the number of errors (patients $Mdn=1.0$, $IQR=2.0$, $n=40$; healthy controls $Mdn=1.0$. $IQR=2.0$ $n=26$), $U=533.5$, $p=.86$).

Correlations between TUG, neuropsychological assessment, and postural measures.

Explorative correlation analyses showed that the TUG task measures (manual and automatic for comparison)

Table 2 Detailed results of intergroup performance comparisons for the neuropsychological assessment

Task	Median, SD, *n* healthy controls	Median, SD, *n* vestibular patients	Mann–Whitney *U* (*p* value), effect-size (rank biserial correlation)	Adjusted *p* value*
DHI – Total	(0.0 ± 3.3), *n* = 26	(30.0 ± 18.5), *n* = 48	**<.001; 0.960**	**.003**
DHI – Physical	(0.0 ± 1.7), *n* = 26	(13.5 ± 6.0), *n* = 48	**<.001; 0.942**	**.003**
DHI – Functional	(0.0 ± 1.5), *n* = 26	(9.0 ± 8.1), *n* = 48	**<.001; 0.913**	**.003**
DHI – Emotional	(0.0 ± 0.5), *n* = 26	(9.0 ± 7.0), *n* = 48	**<.001; 0.970**	**.003**
HADS – Total	(8.0 ± 4.4), *n* = 26	(12.0 ± 5.9), *n* = 48	**.002; 0.438**	**.005**
HADS – Depression	(2.0 ± 2.5), *n* = 26	(4.0 ± 3.4), *n* = 48	**.003; 0.424**	**.007**
HADS – Anxiety	(6.0 ± 2.7), *n* = 26	(7.5 ± 3.6), *n* = 48	**.047; 0.280**	.068
NVI—Total	(57.5 ± 11.9), *n* = 26	(63.0 ± 13.5), *n* = 45	.113; 0.227	.151
NVI – Space perception	(8.5 ± 3.5), *n* = 26	(8.0 ± 3.6), *n* = 45	.305; −0.147	.375
NVI – Time perception	(5.0 ± 1.5), *n* = 26	(6.0 ± 1.9), *n* = 45	.391; 0.121	.447
NVI – Attention	(9.5 ± 3.2), *n* = 26	(9.0 ± 3.0), *n* = 45	.723; 0.051	.771
NVI – Memory	(9.0 ± 2.3), *n* = 26	(9.0 ± 3.2), *n* = 45	.852; 0.027	.852
NVI – Emotion	(8.5 ± 2.6), *n* = 26	(11.0 ± 3.1), *n* = 45	**.011; 0.365**	**.020**
NVI- Vision	(8.0 ± 2.5), *n* = 26	(9.0 ± 2.9), *n* = 45	**.016; 0.342**	**.025**
NVI—Motor	(8.0 ± 2.5), *n* = 26	(10.0 ± 2.4), *n* = 45	**.011; 0.363**	**.020**

Significant effects are represented in bold. DHI: Dizziness Handicap Inventory, HADS: Hospital Anxiety and Depression Scale, NVI: Neuropsychological Vertigo Inventory. **p* value adjusted according to Benjamini and Hochberg procedure (1995) for Mann–Whitney *U* tests

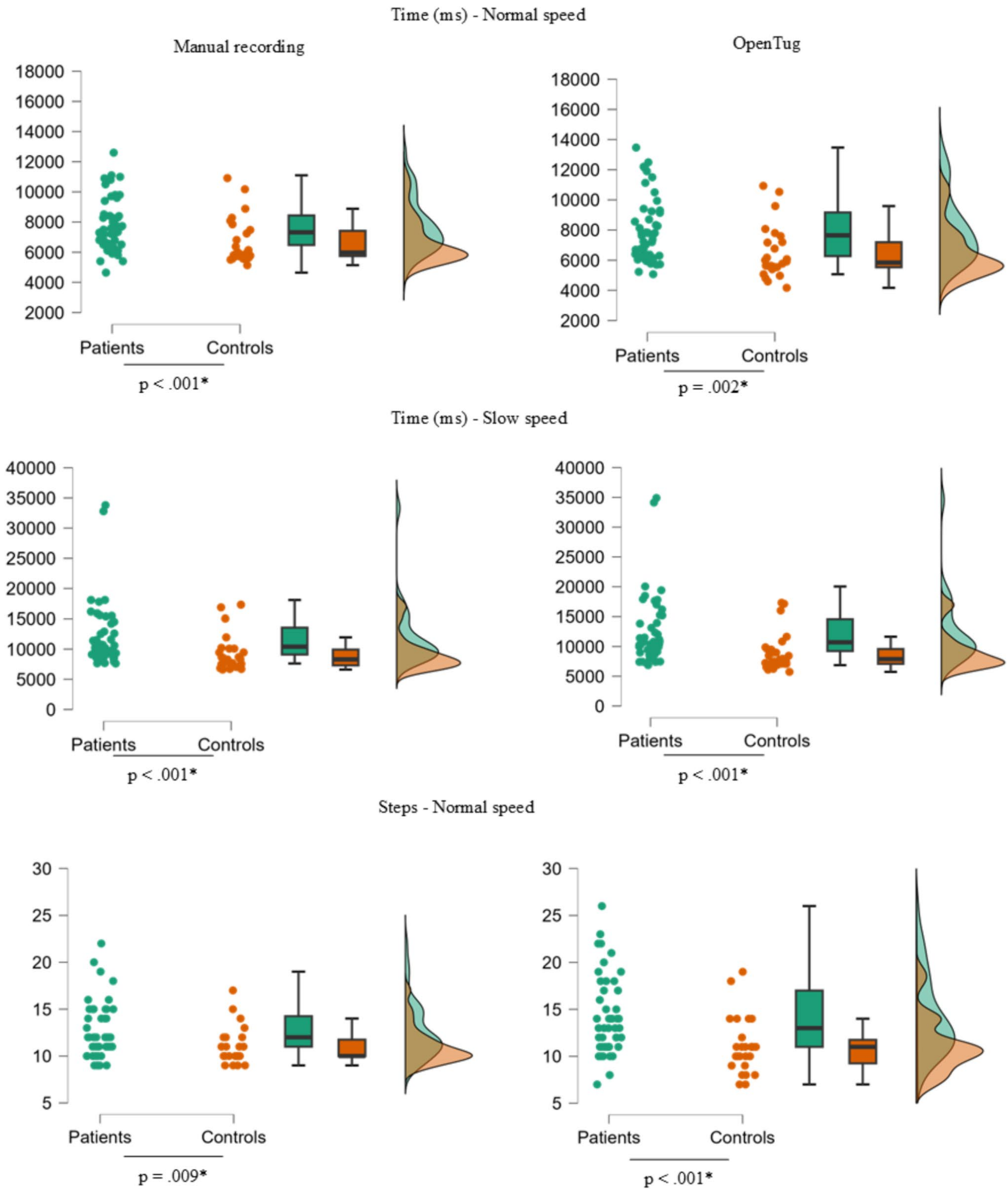

Fig. 1 Raincloud plots of the main significant differences for the intergroup performance comparisons during manual and automatic steps/time analyses of the TUG task at normal and slow speeds

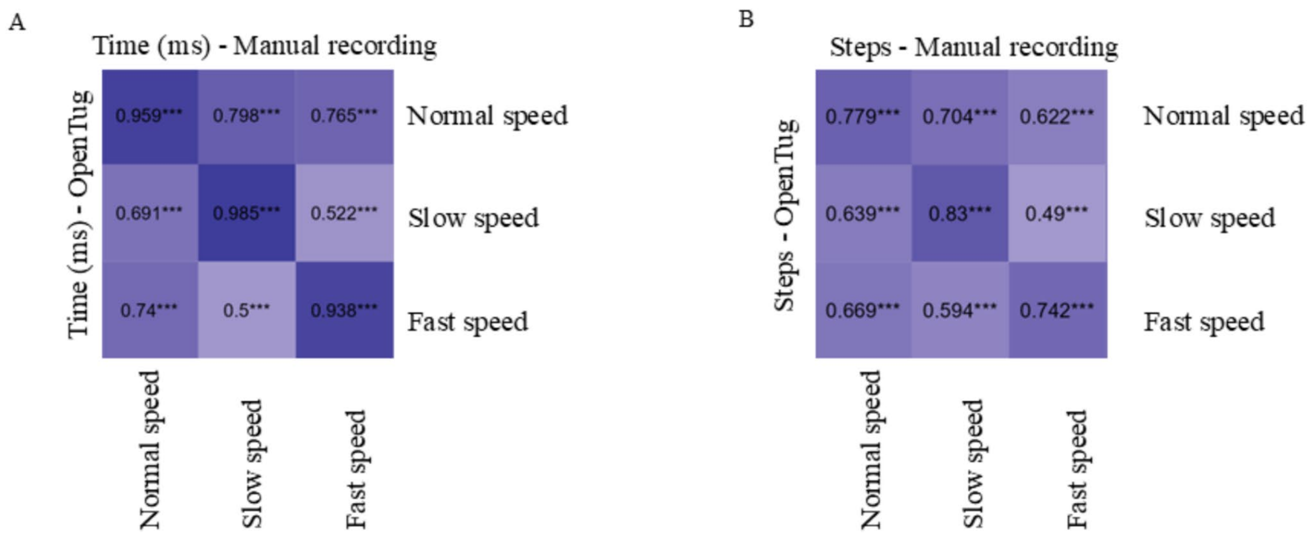

Fig. 2 Correlations between manual and OpenTUG analyses of time (**A**) and number of steps (**B**) in the TUG task. Note. *Darker cells* express greater correlations. ***= $p<.001$

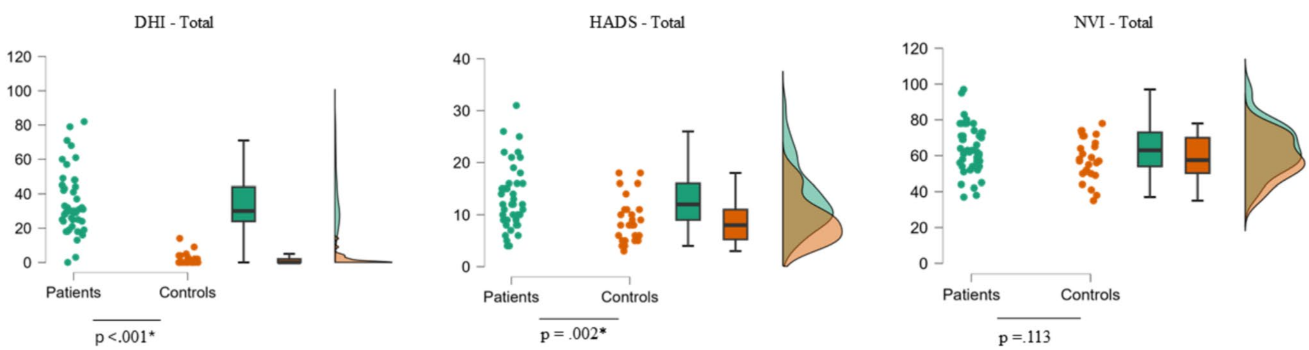

Fig. 3 Raincloud plots of the intergroup performance comparisons for the three main subjective assessments

were linked to subjective and objective neuropsychological assessment. For the subjective assessment, the DHI weakly correlated significantly with all the TUG measures (time and number of steps, manual or OpenTug analyses) (12/12 significant correlations, r_s between.269 and.362). Furthermore, there were very few significant correlations between the NVI and HADS with the TUG (5/12 significant correlations). For the objective assessments, the alertness task moderately correlated significantly with all the TUG measures (time and number of steps) (24/24 correlations, r_s between.305 and.538). For the divided attention task, the TUG task measures correlated significantly almost exclusively with the visual condition (12/12 correlations, r_s between.253 and.540).

For correlations with postural measures, the TUG measures (time and number of steps manually and OpenTUG analyses) correlated partially with the postural assessment of the Framiral Multitest Equilibre, depending on the conditions and the variables measured (time or number of steps). In general, the time taken for performing the TUG task correlates with more postural measures than the number of steps (17/36 vs. 13/36 significant correlations).

Within postural measures, conditions B and D (stable platform, eyes closed; unstable platform, eyes open) correlated significantly with the majority of the TUG measures (17/24 correlations, r_s between.378 and.574). Conditions C (stable platform, eyes open with optokinetic stimulation) correlated significantly with half of the TUG measures (6/12, (r_s between.403 and.511). Conditions A, E, and F (stable platform eyes open; unstable platform eyes closed; unstable platform eyes open with optokinetic stimulation) correlated very few with the TUG measures (7/36 correlations, r_s =.373 and.445). See Fig. 4 for the detailed measures.

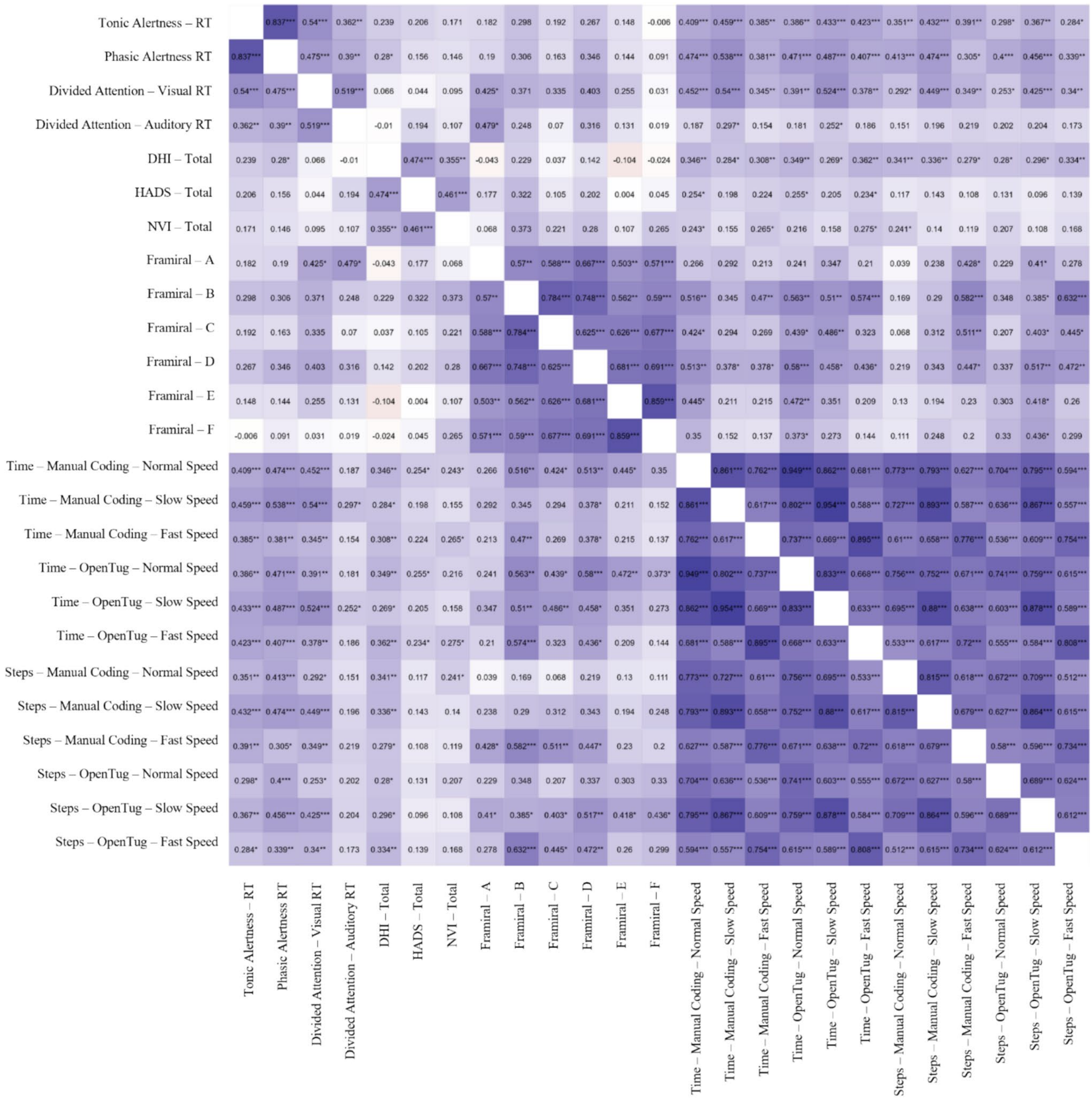

Fig. 4 Heatmap of the correlations between TUG, neuropsychological assessment, and postural measures. Note. *Darker cells* express greater correlations. * $p<.05$, ** $p<.01$, *** $p<.001$

Discussion

To assess the effectiveness of the 2D human pose estimation method (OpenTUG) for vestibular patients, we analyzed the data from 48 individuals with mixed vestibular disorders and 26 mean age-matched healthy controls for their completion of a simple Timed-Up & Go (TUG) task. These data were then correlated with a neuropsychological evaluation including both subjective affective and objective measures. To the best of our knowledge, our results demonstrated for the first time that it is feasible to apply a 2D human pose estimation method, without additional kinematic sensors, to patients with vestibular disorders. Concurrent validity between OpenTUG automatic and manual step/time analyses is supported, as we found similar differences between patient and control group performances. Correlation analyses between automatic and manual steps/time analyses also support this comparison.

Concerning the TUG task, our results align with a previous study by Kim et al. (2021), which found that patients with vestibular disorders (specifically unilateral vestibular deafferentation) required more time than healthy controls to complete the TUG task using body-worn inertial measurement units. Aside from this recent study, most previous research has not directly compared vestibular patients with healthy controls, focusing instead on comparisons between fallers and non-fallers within vestibular populations (Herssens et al., 2021) or pre- and post-rehabilitation evaluations (Brown et al., 2001; Gill-Body et al., 2000; Karapolat et al., 2014).

In addition to those results, the neuropsychological evaluation revealed that, despite ongoing physiological treatments, patients continued to experience significant (although moderate) subjective impacts from their vestibular disorders. Compared to healthy controls, patients reported higher levels of physical, emotional (particularly depressive symptoms), and functional complaints. Correlations between the DHI and the TUG/OpenTUG were generally weak to moderate in strength, yet they were consistent across several measures, and many reached significance, suggesting robust underlying associations. Our results were similar to the significant moderate correlations observed in aged participants with vestibular disorders, with correlations demonstrated between classical TUG measures at usual gait speed and the DHI (Verdecchia et al., 2020).

Interestingly, the cognitive complaints recorded in our studies were less present than the emotional complaints, and no objective cognitive deficits were observed in the patient group. However, during the TUG task, patients took more time and steps to complete the task than controls. These findings were corroborated by the OpenTUG analysis, supporting the validity of applying deep pose estimation to this patient population.

Additionally, previous research has seldom explored the potential connection between TUG performance and neuropsychological assessments in a population with vestibular disorders. The exploratory correlations between TUG performance and attentional measures suggest that automated gait analysis could help detect cognitive difficulties with potential consequences for daily mobility, such as navigating complex environments. Similarly, partial associations with postural instability indices indicate that OpenTUG may complement balance assessments as a rapid and accessible screening tool. While these correlations were weak to moderate, their consistency highlights potential avenues for integrating cognitive and postural dimensions into gait evaluation in vestibular patients. These findings align with prior evidence linking vestibular dysfunction to cognitive and balance outcomes (e.g., Bigelow & Agrawal, 2015; Chari et al., 2022) and extend this work by showing the added value of a low-cost video-based approach. However, patient characteristics likely influence the strength of this relationship. For instance, Bosmans et al. (2022) examined the relationship between bilateral vestibulopathy (BV) and cognitive function in older adults. Unlike our mixed-vestibular disorder sample, their study found significant differences in objective cognitive assessments using the Repeatable Battery for the Assessment of Neuropsychological Status (RBANS-H). However, no association was found between TUG performance and cognitive measures in their population. This suggests that the type of vestibular disorder and the individual's level of compensation may influence the presence or absence of objective cognitive impairments and their relationship with postural stability and walking ability.

Is it about compensation?

In a previous paper, we suggested that Kahneman's Capacity Model of Attention (Egeth & Kahneman, 1975; Lacroix et al., 2021) may explain vestibular patients' neuropsychological and physiological outcomes. According to this model, patients who successfully compensate physiologically would have fewer cognitive resources available, as these would be redirected to maintaining postural control and preventing falls. In our current study, the patients with mixed vestibular disorders were still undergoing physiological treatment, suggesting that they had not yet fully compensated for their vestibular dysfunction. This assumption is supported by their high scores in more challenging conditions of the Framiral Multitest Equilibre (PII-E and F, averaging 4.3 and 4.5), and by their neuropsychological assessments, which did not reveal cognitive deficits, indicating that cognitive resources were probably still available.

Conversely, in Bosmans et al.'s research, their patient's group had a chronic diagnosis of Bilateral Vestibular Loss, according to the Bárány Society criteria. In their case, cognitive deficits were observed, but no association was found with the TUG task. This could suggest that patients who were permanently compensated for their vestibular deficits no longer had sufficient cognitive resources to perform well in objective neuropsychological assessments.

Limitations

While our study provides valuable insights about the application of deep pose estimation algorithms within the vestibular-lesioned patient population, several limitations should be considered when interpreting the findings.

First, the patient group was heterogeneous, including individuals with different vestibular pathologies undergoing rehabilitation. This reflects everyday clinical practice and enhances ecological validity, but it limits direct comparability with studies that focus on more homogeneous diagnostic groups (e.g., unilateral vestibular loss, bilateral vestibular loss, Ménière's disease, vestibular neuritis, vestibular schwannoma). Consequently, the generalizability of our findings to specific vestibular conditions should be interpreted with caution. Future research should therefore include larger samples stratified by diagnosis to determine whether the associations observed here are consistent across vestibular subtypes.

Second, the way we recorded the TUG task introduces methodological differences with classical TUG protocols. For technical reasons, timing began once participants had fully stood up, rather than from the initial seated position. This discrepancy complicates direct comparison with standard TUG cut-offs (e.g., 13.5 s; Brown et al., 2001), which themselves vary with age and methodology (Bohannon & Schaubert, 2005; Kalula et al., 2010; Siggeirsdóttir et al., 2002). This methodological choice may therefore affect the interpretation of absolute time values. Future studies should aim to align recording procedures with gold-standard protocols or provide adapted reference values for video-based analyses.

Third, unlike instrumented TUG (iTUG) approaches using wearable sensors (Ortega-Bastidas et al., 2023), we were unable to segment the TUG into subcomponents (e.g., standing, walking, turning, sitting) because OpenTUG currently operates on 2D video data. This technical constraint, partly related to lighting conditions, prevents the extraction of 3D kinematic information. As a result, our analyses were limited to global time and step counts, which may overlook subtler gait alterations. Future developments in 3D pose estimation and multi-camera setups will be necessary to refine kinematic precision and capture more detailed motor features.

Taken together, these limitations highlight that our results should be interpreted primarily as a feasibility study. They do not yet allow direct clinical cut-offs or broad generalization across all vestibular disorders. Nevertheless, our findings provide a proof-of-concept for the use of deep pose estimation in this field and point toward actionable next steps: multicenter studies with larger stratified samples, methodological standardization of TUG recordings, and technical improvements enabling segmentation and 3D analysis. Such directions will enhance both the validity and clinical applicability of video-based gait assessment in vestibular populations.

Walking towards the future—The contribution of pose detection algorithms to vestibular and movement disorders research

To the best of our knowledge, this is the first study to apply and validate a deep pose estimation algorithm, without additional kinematic sensors, in a population of patients with vestibular disorders performing the TUG task. Our findings demonstrate the feasibility of OpenTUG as a rapid, non-invasive tool to capture clinically relevant gait parameters and highlight significant associations with subjective complaints, neuropsychological performance, and postural stability. By reducing reliance on manual scoring and enabling cost-effective, scalable assessments, such algorithms offer new possibilities for integrating objective gait analysis into both clinical practice and research.

In this preliminary research, we present solely time and step variables. However, as methods progress toward more detailed kinematic estimations (e.g., 3D analyses, segmentation of TUG subcomponents), newly developed algorithms will refine the characterization of motor profiles and support the development of personalized, data-driven therapeutic strategies. Recent studies have started to apply pose detection algorithms in other clinical populations with movement disorders, including Parkinson's disease, multiple sclerosis, and stroke recovery (Kondo et al., 2024; Li et al., 2018; Tan et al., 2019). By automating movement analysis, these systems reveal subtle motor changes that may escape traditional clinical assessments. In the future, the integration of more detailed kinematic measures could help standardize evaluations, minimize human error, and enhance their value as tools for both diagnosis and therapeutic monitoring.

Pose detection systems offer a non-invasive method for assessing movement, making them suitable for application in both clinical and real-world settings. This enables the evaluation of patients in environments where their symptoms may be more pronounced, thereby enhancing ecological validity. Moreover, such systems broaden the scope of research by supporting longitudinal studies that track changes in movement patterns over time, offering insights into the effects of therapeutic interventions and potential correlations with neuropsychological status.

OpenTUG, as a novel pose estimation algorithm, presents an opportunity to refine the assessment of vestibular patients by providing a more granular analysis of movement, thereby improving clinical monitoring and research applications. However, OpenTUG is not a static, finalized tool; rather, pose estimation technologies remain in constant development. Advances in movement science and pose tracking methodologies will further refine estimations of three-dimensional kinematics, mass, size, and kinetics in both human and animal motion (Seethapathi et al., 2019). As artificial intelligence and machine learning drive ongoing improvements in pose detection algorithms, their transformative potential in the study of vestibular and movement disorders will continue to expand. Larger multicenter studies stratified by diagnosis, methodological standardization of TUG recordings, and technical improvements enabling segmented and 3D analyses will be the next crucial steps.

These advancements will not only deepen our understanding of these conditions but will also pave the way for personalized, data-driven therapeutic strategies tailored to individual patients' motor profiles.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.3758/s13428-025-02854-5.

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Authors' contributions Emilie Lacroix: Conceptualization, Methodology, Data collection, Analyses, Resources, Data Curation, Writing (Original Draft), Writing (Review & Editing), Project Administration. Marius Grandjean, Margaux Huyberechts, Lucie Steenbergen: Data collection, Analysis. Seyed Abolfazl Ghasemzadeh, Christophe De Vleeschouwer: Software adaptation, Writing (Review & Editing), Naïma Deggouj: Clinical coordination for patient testing, Conceptualization Writing (Review & Editing). Martin Gareth Edwards: Conceptualization Methodology, Writing (Review & Editing), Resources, Supervision.

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Data availability The dataset and code analyzed in the current paper are publicly available online: Lacroix, Emilie (2025). ABMA study data and code: Lacroix, Emilie (2025). ABMAData_Lacroix_march2025_Final.jasp. figshare. Dataset. https://doi.org/10.6084/m9.figshare.28755407.

Code availability OpenTUG builds on OpenPifPaf (Kreiss et al., 2019) and is available online here: Lacroix, Emilie (2025). OpenTUG.zip. figshare. Software. https://doi.org/10.6084/m9.figshare.28755245.

Declarations

Ethics approval The research procedures were conducted in accordance with the ethical standards of the institutional and national research committee, and in accordance with the 1964 Helsinki Declaration. The study was approved by the ethics committee of Cliniques Universitaires Saint-Luc-UCLouvain (ref: 2021/16MAR/127 and subsequent amendments—B4032021000039 and registered on an open-access clinical trials register (clinicaltrials.gov, ClinicalTrialNumber NCT06739577).

Consent to participate Informed consent was obtained from each individual participant prior to any participation in the study.

Consent for publication All participants provided written informed consent for their data to be published anonymously as a data sheet for reaction time, number of steps, neuropsychological and TUG scores. They also agree that the information could be reported and aggregated in scientific publications and conference proceedings. A specific authorization diffusion has been signed for one participant who agreed to share the video recorded during her TUG task to illustrate the OpenTUG analyses.

Conflicts of interest/Competing interests The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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