Virtual Reality
https://doi.org/10.1007/s10055-021-00521-6

S.I. : VIRTUAL REALITY FOR THERAPY, PSYCHOLOGICAL INTERVENTIONS, AND PHYSICAL AND COGNITIVE REHABILITATION

A virtual reality bus ride as an ecologically valid assessment of balance: a feasibility study

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Received: 31 May 2020 / Accepted: 23 March 2021

Abstract

Balance disorders can have substantial adverse implications on the performance of daily activities and lead to an increased risk of falls, which often have severe negative consequences for older adults. Quantitative assessment through computerized force plate-based posturography enables objective assessment of postural control but could not successfully represent specific abilities required during daily activities. The use of virtual reality (VR) could improve the representative design of functional activities and increase the ecological validity of posturographic tests, which would enhance the transferability of results to the real world. In this work, we investigate the feasibility of a simulated bus ride experienced in a surround-screen VR system to assess balance with increased ecological validity. Participants were first evaluated with a posturography test and then with the VR-based bus ride test, while the reactions of their centre of pressure were registered. Lastly, participants provided self-reported measures of the elicited sense of presence during the test. A total of 16 healthy young adults completed the study. Results showed that the simulation could elicit significant medial–lateral excursions of the centre of pressure in response to variations in the optical flow. Furthermore, these responses' amplitude negatively correlated with the participants' posturography excursions when fixating a target. Although the sense of presence was moderate, likely due to the passive nature of the test, the results support the feasibility of our proposed paradigm, based in the context of a meaningful daily living activity, in assessing balance control components.

Keywords Virtual reality · Balance assessment · Posturography · Ecological validity · Visual motion

1 Introduction

The ability to move upright while maintaining balance has attracted the attention of researchers in different areas, from sports applications to rehabilitation of neuromuscular diseases. Balance disorders or problems maintaining postural balance can have substantial implications on the performance of most daily activities and lead to an increased risk of falls (Salzman 2010), which often have severe consequences for older adults. In the elderly population, these disorders and the resulting falls are a significant cause of long-term functional impairments, disability, injury, mortality, and loss of independence and quality of life (Rubenstein 2006; Salzman 2010). Because balance disorders are common in many neurological diseases, such as Parkinson's Disease, Stroke, and Multiple Sclerosis, their accurate assessment is essential to plan effective rehabilitation treatments (Claesson et al. 2017; Mihara et al. 2012).

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Clinical assessment tools allow for qualitative functional assessment of balance deficits and risk of falls. However, many qualitative tests rely on coarse and subjective rating scales, partial to tester bias, to measure a complex motor behaviour (Mancini and Horak 2010). A system-level approach is needed to identify the fundamental causes of balance deficits and prescribe specific treatment (Mancini and Horak 2010). As balance control is derived from multisensory integration of somatosensory, visual, and vestibular systems, different tests exist, such as the Balance Evaluation Systems Test or the Physiological Balance Profile, which aim to assess each subsystem separately and during intersensory conflicts. The Balance Evaluation Systems Test (Horak et al. 2009) aims to identify which of 6 biomechanical and neural mechanisms of balance control are deficient so that proper rehabilitation can be designed. The Physiological Balance Profile (Lord and Clark 1996) measures five physiological functions to discriminate between fallers and non-fallers. Objective quantitative assessment through computerized, force plate-based, static posturography offers an alternative way to perform balance assessment without some of its drawbacks: variability within and across testers, the subjectivity of the scoring system, and insensitivity to small changes (Mancini and Horak 2010; Tyson and Connell 2009). Dynamic posturography introduces controlled perturbations to selectively manipulate a sensory input of balance control, such as optical flow/vection (Mancini and Horak 2010). However, for community-dwelling older adults, most of the research-based assessments are abstract single-tasks evaluations that do not feature a representative design of functional activities and underrepresent their demands. Furthermore, it is understood that balance training is task specific and does not transfers to tasks with different demands, resulting in its performance increases not being correctly assessed by generic balance tests (Elion et al. 2015; Giboin et al. 2015; Naumann et al. 2015). Consequently, there is a need for instruments that better reflect postural control demands in daily-life situations (Pardasaney et al. 2013). If "*ecological validity refers to the extent to which the environment experienced by the subject in a scientific investigation has the properties it is supposed or assumed to have by the investigator*" (Bronfenbrenner 1977), most of these assessments lack ecological validity, which could hinder their transferability to the real world.

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Advances in Information and communications technologies—ICT, namely in software and hardware, have led to the easy access to technologies that were up to recent years constrained to high-end laboratories and clinics, such as force plates, virtual reality (VR) systems, and physiological computing systems. As discussed previously, force plate-based posturography is an advantageous instrument in the assessment of balance, but its high cost and space requirements are a limitation to their general adoption (Visser et al. 2008). Meanwhile, the low-cost Wii Balance Board (WBB) (Nintendo Co., Ltd., Kyoto, Japan), designed as a console game controller, has reported being similar to laboratory-grade force plates in validity and reliability (Clark et al. 2010; Huurnink et al. 2013). For that reason, posturography systems that use the WBB as a low-cost force plate have been proposed and studied (Clark et al. 2011, 2010; Huurnink et al. 2013; Llorens et al. 2016).

VR simulations provide real-world-like experiences (Bermúdez i Badia et al. 2016; Burdea and Coiffet 2003; Jerald 2015), a realism that is brought by the immersive characteristics of the system (Bowman and McMahan 2007) and subjectively felt by the participants as *presence*, or the sense of *being there* (Jerald 2015). Immersion is the set of objective characteristics of a VR system regarding which senses it extends to, which ones are disconnected from reality (inclusive), how surrounding are the stimulus, the vividness of information, the match between proprioception and virtual information, and self-representation (Slater et al. 1996; Slater and Wilbur 1997). In contrast, presence is a subjective feeling of participants when experiencing VR, modulated by the system, the content of the virtual environment (VE), and the participant's personal traits. The manipulation of the participants' sense of reality during a VR simulation to match the real environment's properties potentially adds to the ecological validity of an experiment and could take us a step closer to the real scenario without its main drawback, lack of control. VR systems of different natures have their advantages. Surround-screen systems such as CAVEs (Cruz-Neira et al. 1992) have large fields-of-view, require limited or no wearable technology, and provide full-body tracking and self-representation (Gonçalves and Bermúdez 2018). While modern occlusive Head-Mounted-Displays (HMD) are visually inclusive and completely surrounding in field-of-regard, they can influence motion and posture due to their added weight to the head (Morel et al. 2015) and have a higher chance of producing dizziness and cybersickness due to head rotation latency (Sherman and Craig 2018). Notwithstanding, VR has been shown to be able to provide standardized, reproducible, and controlled VEs for the assessment of balance (Morel et al. 2015).

In an effort to design an objective and ecologically valid assessment test that could overcome the limitation in the transferability of posturographic results to real-world situations, we developed the "VR Bus Assessment of Balance". The test combines the objective assessment of postural adjustments through measures of the centre of pressure, as in standardized posturographic tests, with sensory stimulation through the recreation of a realistic, meaningful task in an immersive environment, as in VR applications. Our proposed system consists of dedicated software and is implemented on a low-cost VR surround-screen projection system of high immersive characteristics, which can successfully

Journal : Large 10055 | Article No : 521 | Pages : 9 | MS Code : 521 | Dispatch : 30-3-2021

induce presence (Gonçalves et al., n.d.; Gonçalves and Bermúdez 2018). The system is instrumented with a Kinect v2 (Microsoft Corp., Redmond, Washington, USA.), a WBB, and Plux BioSignals (PLUX wireless biosignals S.A., Lisbon, Portugal), and allows the analysis of motion, postural control, electrocardiography, electromyography and electrodermal activity. The VR Bus Assessment of Balance visually simulates a bus ride through the streets of a city, where the participant acts as a standing passenger and is required to maintain balance. By simulating a bus ride, the user is exposed to controlled manipulations of optical flow in a meaningful everyday activity, increasing the ecological validity of the assessment, and, potentially, the transfer of results to real-world situations. While, in terms of ecological validity, this system lacks motion (moving or tilting), haptics, and stimulation of the participant's vestibular system, it compensates it with its simplicity, low-cost devices and safety, which substantially reduces the existing barriers for clinical acceptance and deployment of such an approach. Additionally, not only visual input plays an important role in balance and postural control in the general population bus is of particular importance post-stroke (Bonan et al. 2004; Yelnik et al. 2006; Navalón et al. 2014).

In this work, we investigate the feasibility of the VR Bus Assessment of Balance to assess healthy young adults' balance performance by comparing its results with a validated WBB-based posturography balance assessment battery (Llorens et al. 2016). First, we measure the extent to which participants felt present in the simulated world, which could support the tool's ecological validity. Second, we investigate if this tool can produce observable and significant changes in participants' posture, measured trough reactions of the centre of pressure (CoP) to variations in the optical flow. Lastly, we examine possible correlations between the participants' responses to the simulated optical flow and their individual ability to keep balance.

2 Methods

2.1 Application and VR system

The VR Bus Assessment of Balance was built with the game engine Unity 3D (Unity Technologies, San Francisco, USA). The ride's backdrop is the virtual streets of Reh@City, a grid plan neighbourhood of a city with over 200 buildings, some parks, and other vehicles (Paulino et al. 2019). Reh@City also features billboards and storefronts of real brands and businesses familiar to the study participants, aiming to further increase the ecological validity of the experience. Also, with this aim, the interior of the virtual bus was modelled to resemble a bus of the local urban bus service. The bus ride drives a closed circuit at speeds ranging from 5.7 to 32 km/h. It undergoes several accelerations and decelerations of around 1.5 m/s^2 (0.15 g) and brief breaks of 4.7 m/s^2 (0.45 g). The circuit has nine left turns, and five right turns, with a peak angular velocity from 13 to 16°/s, and it takes approximately 4.5 min to complete (Fig. 1). The sound of the Bus engine and passing cars is implemented coherently with the simulation behaviour.

The experience takes place inside a CAVE, comprising a low-cost VR monoscopic surround-screen projection system of high immersive characteristics, mediated through the KAVE software (Gonçalves and Bermúdez 2018). The display consists of the front projection into the three inside walls and floor of a cube-like structure, where each wall is 2.8 m wide by 2.1 m tall, and the pixel density is approximately 4 pixels per cm. The system uses a Kinect v2 to track the user's head and adapt the immersive projection on the walls and floor to its position in real time. It also features a 5.1 surround sound system.

During the virtual ride, data are collected synchronously at 30 Hz from the virtual bus itself (position and orientation), from a WBB (CoP position over the board), and the Kinect v2 sensor (3-dimensional position of the 25 joints' skeleton). The VR application, together with the system used, and the local bus's interior, are shown in Fig. 2.

2.2 WBB-based posturography system

A WBB-based posturography system, previously validated with 144 healthy adults and 53 individuals with stroke (Llorens et al. 2016), was used in this study to provide a reference assessment of balance. The system includes three standardized assessment protocols, the modified Clinical Test of Sensory Interaction on Balance (mCTSIB), the Limits of Stability (LOS), and the Rhythmic Weight Shift (RWS). The mCTSIB measures mean speed and maximum excursion of CoP in the medial–lateral and anterior–posterior axes for 30 s in 4 conditions, eyes open and closed over a flat surface, and eyes open and closed over foam, to detect sensory impairments during quiet stance. The LOS measures the maximum controlled CoP excursion in 8 directions without losing balance. Lastly, the RWS measures the directional control of participants' CoP when rhythmically following a visual reference in both the medial–lateral and anterior–posterior axes.

2.3 Participants

A convenient sample of participants was recruited from the body of researchers of a research institute. The inclusion criteria were to be 18 years old or older, understand English, no known balance-related injuries or surgery, and no motor or cognitive limitations or epilepsy. A total of 18 people volunteered to participate. The first participant was

Fig. 1 Top view of Reh@city with the bus route in yellow

Fig. 2 Interior of a local bus and the VR Bus Assessment of Balance underway

used to test and rehearse the protocol, and another one failed to follow the instructions during the experiment; therefore, their data were not included for analysis. Sixteen participants, nine women, and seven men, with an average age of 31.3 ± 6.5 years, a weight of 65.53 ± 11.85 kg, and a height of 1.69 ± 0.08 m, completed the study.

2.4 Procedure

Participants performed the experiment individually. First, they were introduced to the experiment, the procedure, and were answered any questions they had; then, they provided their written informed consent. A characterization questionnaire followed this. Their balance and postural control were assessed with the WBB-based posturography system, and a short rest of 2 min followed. Next, they were introduced to the VR surround-screen projection system. Participants were positioned barefoot over the WBB, facing the front wall, 2 m away from it, and aligned with its centre (Fig. 3). They were instructed not to move their feet and keep the arms along the body, other than that they were asked to act as a standing bus passenger over the WBB and were free to look around. After those instructions, they completed the VR bus ride. Lastly, participants were asked to rate their sickness and dizziness on a 1–7 Likert scale and answered the 3-item Slater-Usoh-Steed Questionnaire (SUS) (Slater

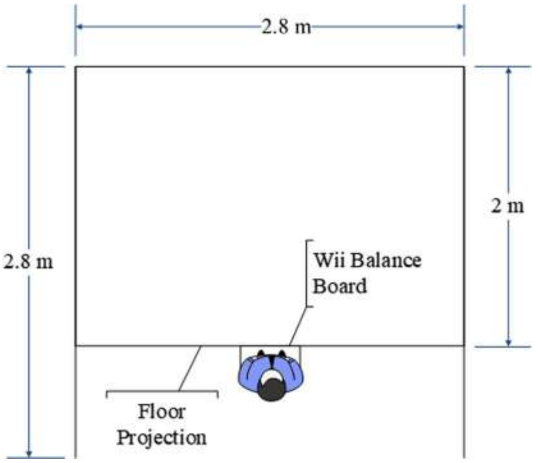

Fig. 3 Top view of the VR system projection surfaces with WBB and participant placement

et al. 1995), and the Presence Questionnaire (PQ), including 19 core items and 3 audio items (Witmer et al. 2005; Witmer and Singer 1998).

2.5 Analysis

Data were analysed in three ways, each corresponding to one of the goals stated in the introduction. First, we report descriptive statistics of the results from the questionnaires regarding presence and cybersickness. Second, the time-series data for each participant experiment were reduced to segments of interest that fitted into 3 types of events, according to the bus trajectory and speed: straight trajectory at constant speed, straight trajectory with speed changes, and turns. For each of the events, three posturography measures were calculated from the WBB CoP position: maximum excursion in the medial–lateral axis, maximum excursion in the anterior–posterior axis, and mean speed. Due to the non-normal distribution of the data, nonparametric tests were used. The Kruskal–Wallis test was used to find if the type of trajectory had a significant effect on the three measures. The Mann–Whitney test with Bonferroni correction was used to follow up on these findings and understand between which pair of trajectory types those differences were significant. Second, for each participant, the same three measures were averaged for events of the same type, to get the participant's average CoP behaviour for straights, speed changes, and turns. Lastly, the correlation between these values and metrics obtained from the posturography evaluation was calculated for each type of event. The significance level used was $\alpha = 0.05$ in all the analyses, and Bonferroni's correction was used to correct for multiple comparisons. The analysis was done using IBM SPSS Statistics 22 (IBM, New York, USA) and MatLab 2013b (MathWorks, Massachusetts, USA).

3 Results

3.1 Subjective evaluation of the VR bus ride

The two questionnaires used to measure the subjective feel of presence experienced by participants evidenced moderate levels of presence reported, as described by a score of 50.72% [3–21] in the SUS and 65.74% [19–133] in the PQ. Individual analysis of the items of the PQ showed that participants rated the interface (projections and Kinect) and sounds of the VR Bus Ride with scores of 88.56% and 78.11% [3–21], respectively, which support the high immersion provided by the system. According to the self-evaluation of performance, rated with 75.5% [2–14], participants found it easy to adapt to the experience. In contrast, factors related to interaction with the virtual environment received lower scores, with the possibilities to act and examine having the lowest scores, being 52.3% [4–28] and 66.3% [3–21]. With a score of 60.57% [7–49], the realism of the experience was found to be moderate and slightly lower than the overall presence score. Finally, the levels of sickness or dizziness reported after the experiment were very low (Table 1). AQ4

Table 1 Descriptive statistical values of the subjective evaluation of the VR Bus Ride experience

Variable	[Range]	Mean ± SD	% of range
Presence SUS	[3–21]	12.13 ± 3.81	50.72% ± 21.17%
Presence Q. (core 19-items)	[19–133]	93.94 ± 19.13	65.74% ± 16.78%
Realism	[7–49]	32.44 ± 9.22	60.57% ± 21.95%
Possibility to act	[4–28]	16.56 ± 6.40	52.33% ± 26.67%
Quality of interface	[3–21]	18.94 ± 2.14	88.56% ± 11.89%
Possibility to examine	[3–21]	14.94 ± 3.09	66.33% ± 17.17%
Self-evaluation of performance	[2–14]	11.06 ± 2.79	75.50% ± 23.25%
Sounds (3-items, not core)	[3–21]	17.06 ± 3.64	78.11% ± 20.22%
Sickness	[1–7]	1.69 ± 1.54	11.50% ± 25.67%
Dizziness	[1–7]	1.88 ± 1.26	14.67% ± 21.00%

3.2 Responses of the centre of pressure during the VR bus ride

The maximum excursion of the CoP in the medial–lateral axis and mean speed were significantly affected by the type of bus trajectory, $H(2)=21.99$, $p<0.05$ and $H(2)=79.46$, $p<0.05$, respectively. In contrast, the bus trajectory did not influence the maximum excursion in the anterior–posterior axis $H(2)=3.42$, $p=0.181$. A pairwise comparison of the three road events for the two affected metrics showed that both had significantly ($p<0.0083$) lower values in the straight trajectory segments of constant speed than during the turns, $U=4904$ and $U=4891$. Again, both had significantly ($p<0.0083$) lower values in straight segments with speed changes than in turns, $U=39{,}310$ and $U=27{,}900$. Neither measure showed differences between straight trajectories of constant speed and straight speed changes, $U=12{,}057$, $p=0.099$ and $U=12{,}369$, $p=0.174$. The bus turns, then, significantly increased maximum CoP excursion in the medial–lateral axis and mean speed, compared to straight trajectories, independently of the acceleration.

3.3 Relation of responses of the centre of pressure during VR bus ride and balance measures

The maximum excursion in the medial–lateral axis and mean speed of the participant's CoP during bus turns significantly correlated ($p<0.05$) with the measures during the eyes-open condition of the mCTSIB. As seen in Table 2, participants with higher medial–lateral excursions in reaction to the bus's virtual turns had a lower maximum excursion when fixating a static target during the posturography assessment. The same was true for straight trajectories with velocity changes. Neither the maximum excursion (in both axis) nor the mean speed of the participant's CoP during straight bus trajectories of constant speed correlated with any relevant metrics assessed by the mCTSIB.

4 Discussion and conclusions

This work evaluated the feasibility of using an immersive simulation of a bus ride, from a passenger perspective, to assess balance and postural control from an ecological valid standpoint. We started by evaluating how much the participants felt present in the simulation and not in a laboratory. Then, we tested if different behaviours of the bus during the visual simulation would produce observable effects on participants' posture. Finally, we explored the relationship between the participants' postural responses to the visual simulation and their posturography results from a validated tool.

Following previous investigations of balance, a surround-screen system was used instead of an HMD to avoid wearing a device on the head, which has been shown to impact balance (Morel et al. 2015), and preserves direct visual feedback of the participants' body. Furthermore, it induces much lower levels of cybersickness, due to lower apparent latency to head rotation (Sherman and Craig 2018); this also helps to mitigate what would be otherwise an uncontrolled element in the simulation. This was confirmed by our results, with participants reporting almost residual levels of sickness and dizziness.

Regarding the examination of the ecological validity of the test through the elicited sense of presence, reports to the SUS in our study were lower than previous experiments performed by the authors in a VR search task with the same system. However, the results from the PQ are much more in line with previous studies' results and even higher than some (Borrego et al. 2016; Gonçalves et al., n.d.). High results for "quality of the interface" and "sounds" indicate that participants valued the system's immersive characteristics and the quality of the three interfacing elements, i.e. visual and audio feedback, and input. However, the Kinect's perspective control was not noticeable, as the bus test required to remain static. Therefore, interpretation of the ratings to the "quality of the interface" might not be obvious. Participants

Table 2 Significant correlations between responses of the centre of pressure during the VR Bus Ride and the modified clinical test of sensory interaction on balance

			Eyes-open condition of the mCTSIB		
			Max. Exc. Ant-Post	Max. Exc. Med-Lat	Mean Speed
VR Bus Ride	Turns	Max. Exc. Ant-Post	ns	ns	ns
		Max. Exc. Med-Lat	− .695	− .523	ns
		Mean Speed	ns	ns	.520
	Straight trajectories with speed changes	Max. Exc. Ant-Post	ns	ns	ns
		Max. Exc. Med-Lat	− .641	− .557	ns
		Mean Speed	ns	ns	ns

ns non-significant

also reported high values of self-evaluation of performance, considering the system easy and quick to adapt to. Again, considering the passive and static nature of the experience, it was expected that both the possibilities to act and examine would have low values, which was indeed the case. Finally, the realism score evidences that maintaining static balance during a real bus ride encompasses multiple and complex perturbances that challenge human balance, which were not considered in the VR simulation. As mentioned in the introduction, balance training has been shown to be task-specific, not transferring to other tasks with different postural demands, and individual balance abilities to be mostly experience and task-dependent. This can lead to the failure of generic balance tests to assess their outcomes and not address the specific postural demands of functional activities of daily living. This knowledge should drive efforts to use more ecologically valid assessments. Resulting in the proper identification of functional balance problems with impact in day-to-day living, that can be used to tailor balance interventions. Consequently, further developments should address any simulation incongruencies, which are essential to understand to which extent our VR Bus simulation is similar and representative of the actual functional ADL, and as such, the behaviour of our participants can be representative of it.

Concerning our crucial goal to assess the feasibility of such a VR-based simulation of a relevant ADL, we found relevant and promising results for assessing balance control, from a dynamic posturography standpoint. Participants behaved differently and coherently when subjected to specific variations of the visual stimuli; when the bus turned, participants responded significantly by adopting anticipatory postural adjustments in the medial–lateral axis. This suggests that the VR test can be used to trigger some anticipatory balance control responses successfully and therefore a useful tool to study balance control.

An analysis of participants' behaviour during the different trajectories of the VR bus ride showed significant correlations with selected measurements of the WBB-based posturography system (Llorens et al. 2016). Participants that were more successful in keeping their excursion low (in both axis) when fixating a static target during the posturography assessment had higher medial–lateral excursions when the VR ride presented them with increased contrary visual and vestibular information. In opposition, people who failed to be misled into a visual perturbation response had higher excursions when evaluated in ideal conditions. This finding suggests that the VR Bus Assessment of Balance tool is sensitive to detect people who have a low weight for visual information when integrating it along with somatosensory and vestibular information for balance and postural control.

These results support our proposed paradigm's feasibility based on a more ecologically valid scenario in the context of a meaningful daily living activity. However, the fact that most responses observed during the VR bus ride were in the medial–lateral axis, and only turns elicited significant responses, revealed the inability of our system to trigger or measure significant anticipatory reactions in the anterior–posterior axis. This can have three explanations: while the amount of perceived motion during turns was enough, the optical flow created in straight segments was not. If this is the case, the simulation can be adjusted by increasing linear acceleration values, narrowing the roads, or lowering the bus. Another alternative is that we did not measure the postural adaptations; in this case, other posturography metrics should be investigated, such as the 25 joint's kinematic data collected by the Kinect v2. Lastly, there is also the unlikely possibility that this visual stimulus is simply not used for anticipatory adjustments.

5 Limitations and future work

While we obtained promising preliminary results, some limitations must be considered. First, by diverging from the abstract test approach and pursuing an ecologically valid test scenario we give the participants freedom to behave naturally. In our study, the participants were free to look around; this freedom certainly had consequences on our results, as head movement can lead to changes in the centre of pressure position. However, limiting head movements would have had an impact on postural control, as it is triggered by the vestibular system in automated responses to compensate for perturbation (Allum et al. 1997).

Second, our system is only able to provide visual and audio cues, and it does not afford physical accelerations or cues to the user's vestibular and proprioceptive systems. Because of this, the results we obtained from the visual turns of the bus cannot be expected to match a real bus ride response of participants, as they are, at most, anticipatory adjustments. Therefore, the lack of a compensatory postural adjustment trigger is the greatest obstacle to ecological validity of the system. While the present system provides highly ecological visual input, future developments should focus on adding motion and pressure-sensitive handholds to test ecological validity further. Also, future results should be compared to CoP displacements during real bus rides.

Third, though we aimed to provide and ecologically valid experience through a visual simulation of a bus ride, we have no evidence that if the visual stimulation of the virtual city was replaced by abstract imagery (keeping the same vection), the results would differ. This should be tested as well.

Lastly, as this study was performed with healthy young adults, we cannot expect the results to be generalized to other populations. However, this feasibility study results encouraged us to follow up with a system re-evaluation in assessing its discriminative properties in older adults with an increased risk of falls, which is the system’s real goal.

Author’s contributions All authors contributed to the study conception and design. Maria Fernanda Montoya and Afonso Gonçalves did material preparation. Data collection and analysis were performed by Afonso Gonçalves. Afonso Gonçalves wrote the first draft of the manuscript, and all authors commented on the following versions of the manuscript. All authors read and approved the final manuscript.

Funding This work was supported by the Fundação para a Ciência e Tecnologia through the AHA project (CMUPERI/HCI/0046/2013), and NOVA-LINCS (UID/CEC/04516/2019), by the INTERREG program through the MACBIOIDI project (MAC/1.1.b/098), by project VALORA, Grant 201701–10 of the Fundació la Marató de la TV3 (Barcelona, Spain) and the European Union through the Operational Program of the European Regional Development Fund (ERDF) of the Valencian Community 2014–2020 (IDIFEDER/2018/029).

Availability of data and material The anonymous data used in this study are available upon request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Code availability The custom software used in this study is not yet available but will be made available in the future.

Informed consent All participants in the study provided their written informed consent.

References

Allum JH, Gresty M, Keshner E, Shupert C (1997) The control of head movements during human balance corrections. J Vestib Res 7:189–218

Bermúdez i Badia S, Fluet GG, Llorens R, Deutsch JE (2016) Virtual reality for sensorimotor rehabilitation post stroke: design principles and evidence. In: Reinkensmeyer DJ, Dietz V (eds) Neurorehabilitation technology. Springer, Cham, pp 573–603. https://doi.org/10.1007/978-3-319-28603-7_28

Bonan IV, Colle FM, Guichard JP, Vicaut E, Eisenfisz M, Tran Ba Huy P, Yelnik AP (2004) Reliance on visual information after stroke. Part I: balance on dynamic posturography. Arch Phys Med Rehabil 85:268–273. https://doi.org/10.1016/j.apmr.2003.06.017

Borrego A, Latorre J, Llorens R, Alcañiz M, Noé E (2016) Feasibility of a walking virtual reality system for rehabilitation: objective and subjective parameters. J Neuroeng Rehabil 13:68. https://doi.org/10.1186/s12984-016-0174-1

Bowman DA, McMahan RP (2007) Virtual reality: how much immersion is enough? Computer 40:36–43. https://doi.org/10.1109/MC.2007.257

Bronfenbrenner U (1977) Toward an experimental ecology of human development. Am Psychol 32:513–531. https://doi.org/10.1037/0003-066X.32.7.513

Burdea GC, Coiffet P (2003) Virtual reality technology, 2nd edn. Wiley, Hoboken

Claesson IM, Grooten WJ, Lökk J, Ståhle A (2017) Assessing postural balance in early Parkinson’s Disease—validity of the BDL balance scale. Physiother Theory Pract 33:490–496. https://doi.org/10.1080/09593985.2017.1318424

Clark RA, Bryant AL, Pua Y, McCrory P, Bennell K, Hunt M (2010) Validity and reliability of the Nintendo Wii Balance Board for assessment of standing balance. Gait Posture 31:307–310. https://doi.org/10.1016/j.gaitpost.2009.11.012

Clark RA, McGough R, Paterson K (2011) Reliability of an inexpensive and portable dynamic weight bearing asymmetry assessment system incorporating dual Nintendo Wii Balance Boards. Gait Posture 34:288–291. https://doi.org/10.1016/j.gaitpost.2011.04.010

Cruz-Neira C, Sandin DJ, DeFanti TA, Kenyon RV, Hart JC (1992) The CAVE: audio visual experience automatic virtual environment. Commun ACM 35:64–72. https://doi.org/10.1145/129888.129892

Elion O, Sela I, Bahat Y, Siev-Ner I, Weiss PL, Karni A (2015) Balance maintenance as an acquired motor skill: delayed gains and robust retention after a single session of training in a virtual environment. Brain Res 1609:54–62. https://doi.org/10.1016/j.brainres.2015.03.020

Giboin L-S, Gruber M, Kramer A (2015) Task-specificity of balance training. Hum Mov Sci 44:22–31. https://doi.org/10.1016/j.humov.2015.08.012

Gonçalves A, Bermúdez S (2018) KAVE: building kinect based CAVE automatic virtual environments, methods for surround-screen projection management, motion parallax and full-body interaction support. Proc ACM Hum-Comput Interact 2:10:1-10:15. https://doi.org/10.1145/3229092

Gonçalves A, Borrego A, Latorre J, Lloréns R, Bermúdez i Badia S, n.d. Evaluation of the tracking reliability, sense of presence, and cybersickness of the KAVE, an open-source software for low-cost virtual reality surround-screen projection systems. IEEE Transactions on Visualization And Computer Graphics Accepted for publication.

Horak FB, Wrisley DM, Frank J (2009) The Balance evaluation systems test (BESTest) to differentiate balance deficits. Phys Ther 89:484–498. https://doi.org/10.2522/ptj.20080071

Huurnink A, Fransz DP, Kingma I, van Dieën JH (2013) Comparison of a laboratory grade force platform with a Nintendo Wii Balance Board on measurement of postural control in single-leg stance balance tasks. J Biomech 46:1392–1395. https://doi.org/10.1016/j.jbiomech.2013.02.018

Jerald J (2015) The VR book: human-centered design for virtual reality. Morgan & Claypool, New York

Llorens R, Latorre J, Noé E, Keshner EA (2016) Posturography using the Wii Balance Board^{TM}: a feasibility study with healthy adults and adults post-stroke. Gait Posture 43:228–232. https://doi.org/10.1016/j.gaitpost.2015.10.002

Lord SR, Clark RD (1996) Simple physiological and clinical tests for the accurate prediction of falling in older people. GER 42:199–203. https://doi.org/10.1159/000213793

Mancini M, Horak FB (2010) The relevance of clinical balance assessment tools to differentiate balance deficits. Eur J Phys Rehabil Med 46:239–248

Mihara M, Miyai I, Hattori N, Hatakenaka M, Yagura H, Kawano T, Kubota K (2012) Cortical control of postural balance in patients with hemiplegic stroke. NeuroReport 23:314–319. https://doi.org/10.1097/WNR.0b013e328351757b

Morel M, Bideau B, Lardy J, Kulpa R (2015) Advantages and limitations of virtual reality for balance assessment and rehabilitation.

Neurophysiol Clin/Clin Neurophysiol Spec Issue Bal Gait 45:315–326. https://doi.org/10.1016/j.neucli.2015.09.007

Naumann T, Kindermann S, Joch M, Munzert J, Reiser M (2015) No transfer between conditions in balance training regimes relying on tasks with different postural demands: specificity effects of two different serious games. Gait Posture 41:774–779. https://doi.org/10.1016/j.gaitpost.2015.02.003

Navalón N, Verdecho I, Llorens R, Colomer C, Sanchez-Leiva C, Martinez-Crespo G, Moliner B, Ferri J, Noé E (2014) Progression of posturographic findings after acquired brain injury. Brain Inj 28:1417–1424. https://doi.org/10.3109/02699052.2014.917200

Pardasaney PK, Slavin MD, Wagenaar RC, Latham NK, Ni P, Jette AM (2013) Conceptual limitations of balance measures for community-dwelling older adults. Phys Ther 93:1351–1368. https://doi.org/10.2522/ptj.20130028

Rubenstein LZ (2006) Falls in older people: epidemiology, risk factors and strategies for prevention. Age Age 35:ii37–ii41. https://doi.org/10.1093/ageing/afl084

Salzman B (2010) Gait and balance disorders in older adults. AFP 82:61–68

Sherman WR, Craig AB (2018) Understanding virtual reality: interface, application, and design. Morgan Kaufmann

Slater M, Linakis V, Usoh M, Kooper R, Street G (1996) Immersion, presence, and performance in virtual environments: an experiment with tri-dimensional chess. Presented at the ACM virtual reality software and technology (VRST, pp. 163–172).

Slater M, Steed A, Usoh M (1995) The virtual treadmill: a naturalistic metaphor for navigation in immersive virtual environments. In: Virtual environments ’95, eurographics. Springer, Vienna, pp 135–148. https://doi.org/10.1007/978-3-7091-9433-1_12

Slater M, Wilbur S (1997) A Framework for Immersive Virtual Environments (FIVE): Speculations on the Role of Presence in Virtual Environments. Presence Teleoper Virtual Environ 6:603–616. https://doi.org/10.1162/pres.1997.6.6.603

Teresa P, Ana F, Bermudez i Badia S (2019) Reh@City v2.0: a comprehensive virtual reality cognitive training system based on personalized and adaptive simulations of activities of daily living. Presented at the The Experiment@ International Conference 2019 (exp. at’19), IEEE, Funchal, Portugal

Tyson SF, Connell LA (2009) How to measure balance in clinical practice. A systematic review of the psychometrics and clinical utility of measures of balance activity for neurological conditions. Clin Rehabil. https://doi.org/10.1177/0269215509335018

Visser JE, Carpenter MG, van der Kooij H, Bloem BR (2008) The clinical utility of posturography. Clin Neurophysiol 119:2424–2436. https://doi.org/10.1016/j.clinph.2008.07.220

Witmer BG, Jerome CJ, Singer MJ (2005) The factor structure of the presence questionnaire. Presence Teleoper Virtual Environ 14:298–312. https://doi.org/10.1162/105474605323384654

Witmer BG, Singer MJ (1998) Measuring presence in virtual environments: a presence questionnaire. Presence Teleoper Virtual Environ 7:225–240. https://doi.org/10.1162/105474698565686

Yelnik AP, Kassouha A, Bonan IV, Leman MC, Jacq C, Vicaut E, Colle FM (2006) Postural visual dependence after recent stroke: assessment by optokinetic stimulation. Gait Posture 24:262–269. https://doi.org/10.1016/j.gaitpost.2005.09.007